Hydrogeologic Investigation of Karst near Askov Lagoons, Askov, Minnesota

Prepared for
Minnesota Pollution Control Agency

15 October 2004

Exponent®

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15 October 2004

Doc. no. BO02699.001 0101 0904 KB22

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1 Introduction

In the 1960s, the City of Askov, Minnesota (the City), constructed a lagoon for waste-water treatment. The lagoon was built on the ground surface by relocating Bear Creek to the southeast and constructing a soil berm around the perimeter. The lagoon was constructed with two cells, the larger cell #1 to the east, and cell #2 to the west (see Figure 7). More recently, the City has placed a moratorium on new sewer hook-ups, because the lagoon has been operating at maximum capacity. The desire of the City to enlarge the lagoon system to accommodate growth, and the recent recognition of sandstone karst underlying the lagoon, has caused the Minnesota Pollution Control Agency (MPCA) to examine the hydrogeology of the site and surrounding areas.

MPCA and Exponent designed an investigation to address several aspects of the karst hydrogeology in the Askov area. The components of this investigation are:

1. Describe the degree of conduit flow versus conventional porous-medium flow in the ground-water system at and around the lagoon.
2. Describe the potential extent of influences of waste water on the ground-water system, including the effects of lagoon leakage, stream leakage, and discrete stream sinks along the discharge stream.
3. Conduct a receptor survey to identify points where ground water and surface water (i.e., springs, seeps, water wells, etc.) may be hydraulically connected to the lagoon or discharge stream.
4. Describe the geologic hazards associated with the current lagoon.
5. In the context of results from steps 1 through 4 above, evaluate the risks associated with any expansion or modification of the current lagoon.
6. Provide recommendations for additional work that would enhance decision-making regarding viable long-term options for future waste-water storage and treatment for the City, and for other communities located in similar geologic settings.

To accomplish these goals, Exponent relied on other professionals to assist with some of the technical services. These professionals included Dr. E. Calvin Alexander, Jr., of the University of Minnesota, for dye-tracing techniques; West Central Environmental Services for water quality analyses; and Rodney J. Ikola, of R.J. Ikola & Associates, Inc., for geophysical investigations.

1.1 Geographic Setting

The City of Askov is located in northern Pine County, in east-central Minnesota (Figure 1). The City is 4 miles east of Interstate Highway 35, and about 90 miles north of the Twin Cities. The sewage lagoon is located at the end of Pioneer Way, about one-half mile south of the city business district (Figure 1).

Bear Creek is the principal surface-water drainage in the Askov area. Modified to be a part of the county ditch system, Bear Creek originates in a wetland about three miles north-northeast of Askov and runs south for about 20–25 miles to the St. Croix River upstream from the confluence of the Kettle River with the St. Croix (Figure 2). Bear Creek does not flow continuously along its reach. Rather, it flows to several swallow holes (a sinkhole that is continuously flooded and receives a continuous flow of water from a stream). One of these swallow holes, known as the Big Sink Hole, is located about 1–1½ miles downstream from the sewage lagoon. Only rarely are flows in Bear Creek high enough to overtop the southwestern rim of the Big Sink Hole and allow continuous flow to the south. A second swallow hole is located about ¼ mile upstream from the lagoon.

The Partridge Creek system is the next surface drainage to the east of Bear Creek. Partridge Creek also drains to the south for about 20–25 miles to the St. Croix River (Figure 2). Surface drainage to the west of Bear Creek is carried by several small, unnamed streams that flow southwest to the Kettle River.

Bear Creek now flows along the base of the southeast berm of the sewage lagoon. It originally flowed through the area now occupied by the lagoon, but was moved during construction in the 1960s. Under normal operations, lagoon effluent is discharged to Bear Creek twice each year. High-water conditions created by intense local rainfall have required that the lagoon be discharged more frequently.

1.2 Geologic and Hydrogeologic Setting

1.2.1 Geology

The bedrock geology of the Askov area consists of Mesoproterozoic volcanic and sedimentary rocks deposited in the Midcontinent Rift System (Boerboom 2001; Boerboom et al. 2002; Figure 3). The rift was formed 1,109–1,087 million years ago (Ojakangas et al. 2001). Basalts were deposited during the extensional phase of rift formation. After extension and vulcanism ceased, the graben continued to subside, which provided a basin for the deposition of an unnamed sandstone, the Fond du Lac Formation, and the Hinckley Sandstone (listed in order from oldest to youngest). Subsequent deformation, including compression, of these sedimentary units is evidenced by high-angle reverse faults that cut through them. The reverse faults, including the Hinckley, Douglas, and Pine faults, generally follow the structural trend of the rift. The reverse faults trend northeast-southwest in the Askov area. The Hinckley Fault is located approximately 2 miles southeast of Askov; the Douglas and Pine faults are located farther to the southeast.

Paleozoic sedimentary rocks crop out in southernmost Pine County and may well have covered the entire county when they were deposited about 523 to 453 million years ago (Mossler and Bloomgren, 1992). However, they have since been removed by erosion, exposing the older

Hinckley Sandstone at the land surface for at least tens and possibly hundreds of millions of years.

The area has been glaciated several times during the last two million years. Glacial landforms and materials present at or near the land surface were created by the Grantsburg and Superior ice lobes during the latest glaciation, 25,000 to 10,000 years ago (Patterson and Knaeble 2002). Glacial materials in the Askov area consist of sandy glacial sediments, sandy end moraine sediments, and stream sediments deposited by the Superior lobe, as mapped by the Minnesota Geological Survey. Glacial deposits are less than 50 ft thick over much of the area around Askov (Figure 4). Greater thicknesses of 50 to 100 ft are located south of the City along the north side of the Hinckley Fault. A buried bedrock valley filled with as much as 200 ft of glacial material is located about 3 miles southwest of the City.

1.2.2 Karst

Geographers originally defined karst as a landscape; i.e., a "terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural waters than is found elsewhere" (Jennings 1971). A karst terrane is distinguished by closed depressions, sinkholes, swallow holes, subterranean drainage along discrete channels opened by solution, springs, and caves. Jennings (1983) later expanded the definition of karst to emphasize the importance of subsurface aquifers in a karst terrane. Karst aquifers are defined as aquifers that exhibit flow in conduits—"a specific type of fluid circulation capable of self-development and self-organizations" (Klimochouk and Ford 2000).

Generally, karst is thought of as being developed in limestone because of the widespread occurrence of that rock type and the relatively high solubility of calcite (calcium carbonate) in water. Silica is soluble in meteoric water, though it is less soluble than calcite. Hence, karst landscapes may also develop in sandstone, given sufficient time.

Ground-water movement in karst systems is typically very rapid compared to other porous geologic systems because of the presence of conduit flow. Because of the high flow rates, karst aquifers are generally considered to be more vulnerable to contamination. This vulnerability is especially critical where karst features, such as sinkholes and swallow holes, provide direct hydraulic connections between human activities and the underlying ground-water system.

Karst features in the Askov area were first brought to the attention of the scientific community by then state representative Doug Carlson (Calvin Alexander, personal communication). The sinkholes were mapped by a joint effort of the University of Minnesota and Pine County Soil and Water Conservation District and formed the basis of Troung's (2000) senior research project and Shade's (2002) master's thesis. That work was published as part of the Minnesota Geological Survey and Minnesota Department of Natural Resources' County Hydrogeologic Atlas C-13 (Shade et al. 2001) and in the Minnesota Geological Survey's Report of Investigations 60 (Shade et al. 2002). That work documented the active karst terrane present in the Askov area.

Shade and coworkers mapped more than 250 karst features at land surface (Figure 5). These features consist of glacial materials piped and collapsed into cavities developed in the Hinckley

Sandstone. The mapped sinkholes are located in an area about 18 miles long by 5 miles wide located on the northwest side of the Hinckley Fault. The Hinckley Fault appears to be a fundamental boundary on the occurrence of sinkholes. Sinkholes were sought but not found southeast of the fault. The sinkhole array may extend further in other directions. Northwest of the Hinckley Fault, on the down-thrown side of the fault, the Hinckley Sandstone is as much as 1,000 to 1,500 ft thick; southeast of the fault, on the up-thrown side, the Hinckley Sandstone is much thinner, with only the basal portion remaining. The dissolution of impure sandstone (i.e., containing less soluble material) can produce significant insoluble residue (Gillieson 1996). Hence, development of sandstone karst requires a relatively clean sandstone country rock (i.e., containing only silica). Apparently, the basal Hinckley Sandstone contains quantities of other minerals sufficient to prevent the formation of solution channels and cavities or to clog any that develop (Terrence Boerboom [Minnesota Geological Survey], personal communication). Hence, karst is apparently not well-developed southeast of the Hinckley Fault.

1.2.3 Hydrogeology

Quaternary sand and gravel aquifers do not exist in the Askov area. The water table occurs in the first bedrock unit, the Hinckley Sandstone (Berg 2004b).

The Hinckley Sandstone aquifer provides water supply to the City of Askov and individual, residential wells in the area. Secondary porosity is an important factor in the relatively high hydraulic conductivity of the Hinckley aquifer in the Askov area (Berg 2004a). For example, the City’s municipal wells were designed to intercept as many near-surface fractures as possible, to provide a favorable yield (James de Lambert [Bruce Liesch & Associates], personal communication). Two other geologic units, the Fond du Lac Formation and an unnamed sedimentary unit, underlie the Hinckley Sandstone (Boerboom 2002). These lower units have water quality that is too poor for domestic or industrial use. Basalts associated with the Midcontinent rift underlie these units.

As mapped by Berg (2004a) from data that are considered sparse for the purpose of this study, ground water generally flows to the west, southwest, and south in the Askov area. Depth to ground water is approximately 25 ft as measured in four monitoring wells installed near the lagoon. Based on well logs for some of the residential wells near the lagoon, depth to ground water is approximately 50 ft. Depth to bedrock averages 41 ft for the same wells (Table 1). Regionally, ground water discharges to the south-draining Kettle River, which comes as near as 2½ miles west of Askov.

Ground-water samples from the Askov area have high (three samples) to moderate (one sample) levels of tritium, indicating that rapid recharge from the surface occurs in the Hinckley Sandstone. This is consistent with the expected permeability of the thin, sandy loam surficial material. A chloride/bromide ratio from one sample is sufficiently high to be attributable to human activities, which also indicates relatively rapid recharge. Consequently, the single aquifer in the Askov area is generally mapped as having a “very high” sensitivity to pollution (Berg 2004b; Figure 6). This rating means that contaminants released at the land surface may reach the water table in one month or less.

2 Field Activities

On 31 March 2004, West Central Environmental Services and Dr. Alexander collected water from the lagoon for laboratory analysis. En Chem and Dr. Alexander performed the analyses to obtain background information regarding the presence or absence of natural or man-made fluorescent dyes present in the local ground-water system.

Prior to field activities that began on 12 April 2004, Dr. Alexander and Scott Alexander, of the University of Minnesota, identified seven sites in surface water that would be monitored for the appearance of dyes used in the dye traces. At the same time, Dr. James Piegat, of Exponent, tentatively identified residential wells that would be monitored for the appearance of the dyes, subject to landowner permission.

During the period of 14–17 April 2004, Dr. Piegat obtained permission to monitor 19 wells as part of the dye test. One monitoring point was in the City of Askov municipal water system, and the other 18 stations were residential wells. Charcoal detectors ("bugs") were installed in these wells. For the duration of the dye traces, bugs retrieved from wells and surface-water sites were analyzed in the laboratory by Dr. Alexander and Scott Alexander during the time between retrieval and the next round of installation.

West Central Environmental Services installed four monitoring wells around the lagoon prior to 21 April 2004. These wells were routinely monitored for the appearance of dyes used in the traces and to document ground-water levels. They were sampled once for water quality.

On 23 April 2004, Scott Alexander injected two dyes, one in a sinkhole and one in the discharge of lagoon effluent, to begin the dye traces. On the same day, Rodney Ikola, of Rodney J. Ikola and Associates, and Dr. Piegat conducted a geophysical investigation near the lagoon to determine the suitability of electromagnetic and self-potential methods to identify karst features in the subsurface.

Dr. Piegat conducted the routine changing of bugs from April through August 2004. Twelve additional residential wells were added to the monitoring network in response to the detection of dyes in some of the initial bugs. Dr. Piegat also measured the water levels in each monitoring well and, using a temporary staff gauge, the water level in the Big Sinkhole, each time the bugs were changed.

Beginning on 28 May 2004, West Central Environmental Services and Dr. Alexander sampled residential wells in which the presence of dye was confirmed for analysis of water chemistry. Ground-water sampling and analyses of the four lagoon monitoring wells, lagoon effluent, and the Big Sink Hole were conducted after the dye traces had begun.

During July and August 2004, Rodney Ikola completed a geophysical investigation around the lagoon using the self-potential method.

2.1 Monitoring Well Installation

Four monitoring wells were installed in or near the berm around the lagoon (Figure 7, Table 2) by West Central Environmental Consultants. The purpose of the wells was to monitor movement of dye from the sinkhole immediately to the west of the lagoon. Three of the wells (W20, W21, W22) were drilled as close as possible to the road on the top of the berm that contains the lagoon on the outside slope of the berm. The fourth well (W23) was drilled in the ditch along Pioneer Way about 450 ft northeast of the lagoon. The logs for the monitoring wells show 12–15 ft of clayey sand at the surface, which is underlain by 7½–16 ft of sand on top of sandstone bedrock (Appendix C). The log for W21 reported that the auger bit dropped 2 ft within the upper 5 ft of the sandstone. The drop of the bit indicates that the hole encountered a relatively large fracture, which is consistent with a karst formation.

2.2 Dye-Trace Activities

2.2.1 Introduction

Karst terranes contain discrete features such as sinkholes, swallow holes, and fractures enlarged by solution that transmit water at rates much higher than are possible in a porous medium. It can be difficult, if not impossible, to locate all of these features and understand their interconnectedness in a karst terrane, particularly if glacial deposits overlie the karst as is the case at Askov. This knowledge is vital to understanding ground-water flow patterns, and can be acquired most efficiently by dye-tracing techniques.

Dr. Alexander and Exponent conducted two dye tests. One test injected Rhodamine WT, a red dye, into sewage lagoon effluent to determine the fate of that effluent under normal conditions. A second test injected fluorescein, a different, green dye, into a sinkhole immediately adjacent to the sewage lagoons to assess the fate of lagoon effluent discharged under high-flow conditions and the possible fate of effluent under a hypothetical failure of the lagoon.

2.2.2 Dye-Trace Monitoring Network

A dye-trace study consists of injecting a tracer, fluorescent dyes in this case, into surface or ground water and then measuring the time it takes for them to reach down-flow stations. Stations typically consist of surface-water sampling points such as springs and creeks, and ground-water sampling points such as wells. One advantage of using fluorescent dyes is that small packets of charcoal, called “bugs,” can be placed in the water at a sampling station and changed several days or weeks later. The charcoal adsorbs and concentrates the low concentrations of dye that flow through the bug while it is in the water. The bugs serve as passive, integrating samplers. The bugs are then taken to a laboratory where the dye is extracted and analyzed. Details of bug monitoring and analysis are provided in Appendix A.

For these traces, dyes were injected at two discrete points on 23 April 2004. Movement of the dyes was monitored by a network of bugs placed at selected surface-water points and in the water systems of selected homes. Bugs were replaced every week during April, May, and June; they were replaced every two weeks during July and August.

During the week of 14 April 2004, bugs were installed in three springs along the Kettle River about 2½ miles west of Askov (Figure 8 and Table 3). Three additional bugs were installed in selected creeks (Partridge Creek, Bear Creek, and an unnamed creek where they crossed Pine County Road 30 about 4 miles south of Askov). These six bugs were placed at locations where ground water in the Askov area is anticipated to discharge to surface water.

During that same week, four additional bugs were placed along Bear Creek (Figure 9). Two were placed upstream at the crossings of Minnesota State Road 23 and Pine County Road 32 as controls. Two were placed downstream of the lagoons, one at the crossing of Bear Creek at Pine County Road 142 and one just upstream from the highest expected level of the Big Sink Hole.

Also during the week of 14 April 2004, 19 bugs were installed in individual water systems, including the Askov municipal system (Figure 9 and Table 3). These locations were chosen by identifying landowners who lived within 1 mile of either the sewage lagoons or the Big Sink Hole.

This first round of 29 bugs, installed on 14–17 April 2004, was collected on 21–22 April to provide background information.

On 21 April 2004, bugs were installed in each of the four monitoring wells constructed at the lagoon area, and in the water systems of two additional homes at the request of the landowners (Figure 9). The scheduling of the monitoring well installation and the start of the dye trace prevented background sampling in the monitoring wells.

On 25 May 2004, six additional bugs were installed in systems near well W02 after dye was detected in that system (Figure 9). On 1 June 2004, three additional bugs were installed in systems considered to be downstream from well W02 (W33, W34, and W36; Figure 9). On 15 July, one bug was installed in another system (W35), also considered to be downstream from well W02 (Figure 9).

All monitoring of bugs ended on 27 August 2004.

2.2.3 Lagoon Discharge

Under normal conditions, the lagoon is discharged to Bear Creek twice per year. On 23 April 2004, about 2 L of 20-wt.% Rhodamine WT solution (441.5 g of dye) was added to the normal discharge of lagoon effluent. The dye injection was done at the outlet structure of lagoon cell number two (the smaller, western cell; Figure 7). Approximately one million gallons of effluent were discharged to Bear Creek. The dye was visibly traced as it flowed down Bear Creek to the Big Sink Hole (Figure 9). Under normal conditions, which prevailed at the time of dye injection, all of the flow of Bear Creek, and hence all of the lagoon discharge, enters the ground-water system at the Big Sink Hole.

2.2.4 Sinkholes Near the Lagoon

On 23 April 2004, about a liter of 35-wt.% fluorescein solution (412.8 g of dye) was injected into a sinkhole (MN58:D0055,referred to as D55), located about 130 ft to the west of the lagoon (Figure 7). Sinkhole D55 is flooded by water from Bear Creek during high flows in the creek. The dye was washed into the sinkhole with 3,000 gallons of water provided by the City fire department. The first 1,500 gallons were run into D55 at 15 gallons per minute, which was the rate that the sinkhole drained water. The remaining 1,500 gallons were then flooded into the sinkhole and allowed to infiltrate.

2.3 Water Quality Analyses

Water was sampled at locations where the presence of dye was confirmed. This included three sampling events of the lagoon proper, and two sampling events of surface water from the Big Sink Hole (Table 4). The first water samples were analyzed by En Chem. The suite of organic and metal analytes was chosen from a list on the Minnesota Department of Health (MDH) website. The particular analytes that were measured were those for which En Chem had been certified under MDH's Clean Water Program. Subsequent analyses were performed by Northeast Technical Services (NTS) and by Dr. Alexander.

2.4 Geophysical Activities

A geophysical study of the area immediately around the sewage lagoon was proposed to identify potential karst features in the subsurface that might cause a catastrophic failure of the lagoon. Two geophysical studies had been conducted previously in the Askov area. Bruce Liesch & Associates (1987) conducted a resistivity and seismic survey to identify suitable sites for a municipal well field for the City. Benson and Alexander (1998) used electromagnetic and ground-penetrating radar surveys to investigate karst features on a large parcel adjacent to the lagoon. Neither study produced results useful to this study.

During the week of 19 April 2004, Rodney Ikola, of R.J. Ikola and Associates, Inc., conducted electromagnetic and self-potential surveys to determine whether either method could identify karst features through the relatively thick (~30 ft) overburden of glacial material.

The initial survey was conducted along a line perpendicular to a line of three closely spaced sinkholes located about 200 ft to the west of the lagoon (Ikola 2004a). The electromagnetic survey failed to detect any increase in conductivity where the survey crossed the line of sinkholes. Hence, this technique was not used further.

The self-potential survey did detect a notable self-potential low at the three known sinkholes. The self-potential technique was then used to complete a survey of the area around the lagoon in July and August 2004 (Ikola 2004b). Survey lines were established around the perimeter of the lagoon and in an area extending as much as 400 ft to the northwest of the lagoon. Further information on the methods, equipment, and line locations for these two geophysical investigations are contained in Appendix B.

3 Results

3.1 Dye Trace

The results of the dye-trace analyses are summarized in Tables 5a and 5b. Hard copies of the individual spectra from each dye analysis have been filed with the Minnesota Pollution Control Agency.

3.1.1 Lagoon Discharge

Under normal conditions, the lagoon is discharged to Bear Creek twice per year. The injection of Rhodamine WT to the normal discharge of lagoon cell #2 on 23 April 2004 was designed to help address three issues raised by MPCA: 1) compare conduit flow with porous-medium flow in the local ground-water system; 2) determine the extent of the influence of waste water on the ground-water system at normal stream flow; and 3) identify receptors that may be hydraulically connected to the lagoon or discharge stream.

The dye was visibly traced as it flowed down Bear Creek to the Big Sink Hole (Figure 9). Dye visible to the eye took three hours to travel approximately 3,100 ft down Bear Creek from the lagoon cell #2 outlet structure to the location of bug X07, immediately upstream from the Big Sink Hole.

No Rhodamine WT was found in the first round of bugs that were installed and removed prior to dye injection (Table 5a). As would be expected, Rhodamine WT was detected in the second round of bugs from the Bear Creek crossing of Pine County Road 142 (X03) and from Bear Creek just upstream from the Big Sink Hole (X07) (Figure 10, Table 5a).

Rhodamine WT concentration in both X03 and X07 was highest in bugs collected four days after dye injection; subsequently, the dye concentration declined (Figure 10, Table 5a). Dye detected at X07 was consistently higher in concentration and persisted longer than for X03. Bugs from both sites collected 25 days after dye injection showed a temporary rise in concentration; the bug from X07 collected 84 days after dye injection showed another temporary rise in concentration.

Rhodamine WT was detected in the bug from W02 collected 25 days after the test began (Figure 11, Table 5a). Dye concentration in W02 then rose during the next three weeks and has since been generally declining (Figure 11). This well is located about 0.9 miles southwest of the Big Sink Hole. In response to this detection, ten additional bugs were installed in the area surrounding W02 (W26, W27, W28, W29, W20, W31, W33, W34, W35, and W36). Of those ten bugs, Rhodamine WT was eventually confirmed in only one, W26, which is located about 0.3 miles south of W02. Rhodamine WT in W26 was first detected 60 days after the test began; the concentration peaked one week later and declined to below the detection limit three weeks after the first detection.

There are suggestions of Rhodamine WT in two other wells (W27 and W28) near W02 and W26, but presence of the dye could not be confirmed (Figure 11, Table 5a).

Rhodamine WT was not detected in any other wells or in any surface-water monitoring sites.

3.1.2 Sinkholes Near the Lagoon

Under normal conditions, the lagoon contains a considerable quantity of partially treated sewage. Collapse of part of the lagoon into a sinkhole would release that sewage directly into the ground-water system. Under conditions of high flow in Bear Creek, the creek overflows its bank and drains into the sinkholes immediately west of lagoon cell #2 (Figure 7). Some portion of the effluent released during periods of high flow in the creek may enter those sinkholes and reach the ground-water system.

It is significant to note that the water table under the lagoon is significantly higher than elsewhere in the area (Table 1). This means that the lagoon is a source of ground-water recharge. The water table configuration precludes a remote source of the bacteria discovered in the monitoring wells (Table 8a); they came from the lagoon. This means that not only is the lagoon leaking, but it is leaking at a rate so fast that bacteria survive the trip through the lagoon liner and wind up in ground water. Within the accuracy of the survey methods used, the water table under the lagoon appears relatively flat. Immediately northeast of the lagoon, shallow ground water appears to flow northeast under a low horizontal hydraulic gradient (i.e., typically <0.003 ft/ft).

Injection of fluorescein dye into a sinkhole located about 130 ft west of lagoon cell #2 on 23 April 2004 was designed to help address four issues raised by MPCA: 1) compare conduit flow with porous-medium flow in the ground-water system; 2) determine the extent of the influence of waste water on the ground-water system at high stream flow; 3) identify receptors that may be hydraulically connected to the lagoon or discharge stream; and 4) conduct a failure-probability analysis on the current lagoon, or an assessment of the geologic hazards associated with the current lagoon.

Fluorescein was found on one of the background bugs (W15; Table 5b). However, this detection was not duplicated in subsequent bugs during the test. There are other examples of apparent, but unconfirmed detections of fluorescein (W01, W08, W20, and W25; Table 5b). These detections have no satisfactory explanation; they may reflect dye from other sources, such as releases of automobile coolant or contamination either in the laboratory or during bug installation and retrieval.

Fluorescein has not appeared in any of the bugs located in springs (A09, A10, A11), stream crossings of Pine County Road 30 (X04, X05, X06), or Bear Creek upstream from the lagoon (X01, X02) (Figures 8 and 9, Table 5b). Downstream from the lagoon, fluorescein was indicated in bugs collected from Bear Creek upstream from the Big Sink Hole (X07) between 39 and 67 days after injection (Figure 12a), but not in the bug at the Bear Creek crossing of Pine County Road 142 (X03). This pattern matches that for Rhodamine WT, in that the concentrations of both dyes in X07 are much greater than in X03 (Figure 12b) (fluorescein was not detected at X03). However, fluorescein appears in X07 only during that time between two minor peaks in Rhodamine WT concentration detected by bugs collected 25 and 84 days after injection of both dyes. The period of time between the collection of bugs 25 and 84 days after dye injection is marked by increased precipitation, as reflected in the rise in ground-water elevations measured in the four monitoring wells (W20-W23) and in the stage of the Big Sink Hole (Figure 13, Table 6).

Fluorescein appeared in the first bugs collected from three of the four monitoring wells installed around the lagoon (W21, W22, and W23; Figure 14a, 14b, Table 5b). These bugs were installed on 21 April, the fluorescein was injected on 23 April, and the initial set was changed on 27 April. The concentration in W23, located farthest from the injection point, was at a modest level in the bug collected four days after injection, peaked in the bug collected the next week, and then dropped below the detection limit in the bug collected the following week, where it has remained (Figure 14b). Similarly, fluorescein was found in W20, located on the south side of the lagoon, 19 days after dye injection, but was not confirmed by a second detection. Fluorescein was strongly present in W21 four days after dye injection. The dye peaked 19 days after injection, declined to about one-third of the maximum value by the following week, and remained relatively constant and strongly present through the end of sampling. In W22, located on the north side of the lagoon, the concentration peaked 47 days after injection, declined to 27% of the maximum value by the following week, and has remained relatively constant since then. Fluorescein moved to the east-northeast under the northern part of the lagoon to reach the monitoring wells. A recharge mound produced by the water used to flood the sinkhole could have driven this flow.

Fluorescein was detected in five residential wells: W06, W07, W10, W19, and W25 (Figure 15, Table 5b). All of these wells are west of D55 and document a flow direction directly opposite to the flow indicated by the lagoon monitoring wells. This divergent flow was probably caused by mounding of the potentiometric surface beneath D55 from the 3,000 gallons of water injected with the dye.

The concentration of fluorescein increased with time in wells W06, W07, W10, and W19 (although there is only one observed detection for W19) (Figure 15, Table 5b). In well W25, fluorescein was indicated by two bugs early in the study (bugs collected 4 and 19 days after injection, but not in the bug collected after 13 days), and was detected by the bug collected 60 days after dye injection. The concentration then rose during the period from 60 to 84 days after injection, decreased by an order of magnitude during the subsequent week, and has since increased to levels observed at the end of the test.

The single detection of fluorescein in well W19, located northwest of the lagoon, in the last week of the study is problematic. This detection was not confirmed by a second detection in a following round of bugs, because the test had ended. It is possible that the dye has another source. If the dye did come from the test, then it must have moved through a solution-enlarged conduit. This conclusion is based on: 1) the relatively rapid rate of movement (44 ft/day); 2) the lack of dye in W18, which is half the distance to the injection point and slightly off the line between the injection point and W19; and 3) the correlation in the direction of a line from the injection point to W19 and one of the principal fracture directions measured in the Hinckley Sandstone (Figure 16).

3.1.3 Summary of Dye Results

The mean velocity of Rhodamine WT from the Big Sink Hole to W02 was approximately 188 ft/day. This flow velocity is assumed to represent the leading edge of the dye pulse. This velocity is not consistent with porous-medium flow. A line drawn through W02 and parallel to the Hinckley Fault (1.4 miles to the southeast) passes very close to both the Big Sink Hole and other sinkholes immediately to the west of the sewage lagoon (Figure 16). The observed pattern suggests that Rhodamine WT, and the sewage lagoon effluent into which it was injected, entered the Big Sink Hole and flowed to the southwest along a major, solution-enlarged fracture that is parallel to the Hinckley Fault.

However, the velocity of 188 ft/day is slower than might be expected in a mature limestone karst. There are several possible explanations, including: 1) less solutional enlargement of the sandstone fractures; 2) W02 is not located directly along the major fracture, and some porous-medium flow has occurred in response to pumping by that well; 3) the hydraulic gradient is too low to allow higher velocities; 4) the fracture is not continuous but is a series of en echelon fractures, requiring porous-medium flow from one to the next; or 5) the fractures have been partially clogged by glacial sediments. The delayed appearance of Rhodamine WT in W26 may suggest that there was some porous-medium flow to that well.

The fluorescein that was washed into Sinkhole D55 moved east-northeast under the northern edge of the lagoon. Dye was present in monitoring wells W21, W22, and W23 the first time the bugs were changed, 27 April, after the dye was injected on 23 April (Figures 14a, 14b). The travel time to all three monitoring wells was less than four days. These dye detections document the presence of rapid flow paths to the east-northeast under the lagoon itself. Only lower limits can be placed on the flow velocity of shallow ground water under the lagoons. The highest lower limit, >281 ft/day, is based on travel time for the fluorescein detected in W23 on April 27 (Table 7). The dye that reached W23 flowed past W21 and W22, and therefore, the >281-ft/day velocity also applies to W21 and W22.

The fluorescein washed into Sinkhole D55 also reached a broad "fan" of residential wells to the west but missed other wells in the same direction. Such a pattern is inconsistent with porous-medium flow but is a widely documented phenomenon in fractured and conduit aquifers. The average flow velocity to the first four residential wells with confirmed fluorescein detections is 30 ft/day. This velocity is lower than that yielded by the Big Sink Hole to W02 trace and may indicate a mixture of rapid flow through conduits and a short but much slower flow through a porous medium from the conduit to the individual well. It is unlikely that an individual well is drilled directly into a solution-enlarged fracture conduit. The short time between dye injection and the appearance of fluorescein in wells W06 and W25, and perhaps W07 and W10, indicates that fracture flow is likely a significant mode of ground-water flow, if not the dominant mode, in the vicinity of the lagoons (Figure 17). Fluorescein in W19 can be explained only by fracture flow or by a second source of fluorescein.

Well W06 is located very close to a line drawn parallel to the Hinckley Fault and through the sinkhole in which the fluorescein was injected. This is the same line that passes near the Big Sink Hole and well W02 in which Rhodamine WT was detected (see discussion above). It is possible that flow along a major fracture along this line is relatively fast and that the delay between time of dye injection and appearance in some of the wells nearby is related to a slower, porous-medium flow perpendicular to the trend of the major fracture. However, fluorescein was not detected in well W02. This suggests that the proposed fracture system located along a line from W02 to the lagoon is not uniformly transmissive. There was sufficient time during this study for fluorescein to move from the Big Sink Hole to W02 if fluoroscein was present in the Big Sink Hole. Apparently, there are restrictions to flow in this proposed system of fractures between W06 and the Big Sink Hole. These restrictions may be caused by infilling with glacial material, offsets of fractures, and lack of solutional opening.

3.2 Water Quality Analyses

Results of water quality analyses are shown in Tables 8a and b. None of the analyses for residential wells exceeded any of the Maximum Contaminant Levels set by the U.S. Environmental Protection Agency (EPA). In particular, no fecal coliform bacteria were found in any of the residential wells tested. It should be emphasized that the suite of analytes was selected from the Clean Water Program regulations, which are not designed to characterize drinking water supplies. Hence, this work was not intended to evaluate whether or not water from these wells is safe to drink.

Perhaps the most significant result is the presence of fecal coliform bacteria in the three monitoring wells (W20, W21, W22) drilled through the berm around the lagoon. This result indicates that the lagoon liner is leaking, and at a relatively rapid rate. The fact that the water table under the lagoon is higher than in surrounding areas precludes movement of bacteria from another source to the area around the lagoon.

3.3 Geophysics

The results of the self-potential geophysical survey are shown in Figure 18 (Ikola 2004b). There are several areas of low self-potential anomalies near the lagoon; these are generally located over karst features. A major self-potential low oriented northeast-southwest extends beneath both lagoons from the northern portion of the east lagoon cell through the southwestern portion of the west lagoon cell. This area also exhibited some interference from lagoon infrastructure (e.g., buried piping, berm soils), but the trend was strongly supported by many survey readings. Two other self-potential lows areas are oriented west-northwest to east-southeast. One extends from the northern portion of the west lagoon cell, and the other extends from the northwestern portion of lagoon cell #1. Both of these areas were found to contain sinkholes. These two orientations are parallel to the joint pattern in the Hinckley Sandstone measured by Boerboom (2002). The correlation of self-potential results with known sinkholes and with known joint orientations supports the hypothesis that relatively higher conductivity voids exist beneath the lagoon site. This result is consistent with the rapid flow of fluorescein from D55 to the monitoring wells (W20, W21, W22, and W23). Further discussion of the geophysical survey results is presented in Appendix B.

4 Conclusions and Implications for Future Work

4.1 Conduit vs. Porous-Medium Flow

The water table evaluated in this study is within the Hinckley Sandstone. The velocity of ground-water flow within the aquifer indicated by the movement of Rhodamine WT from the Big Sink Hole to wells to the southwest was approximately 188 ft/day. The velocity of ground-water flow indicated by the movement of fluorescein from a sinkhole adjacent to the lagoon east to monitoring wells drilled through the northwest lagoon berm and northeast of the lagoon was greater than 281 ft/day. The velocity of ground-water flow indicated by the movement of fluorescein to the west, southwest, and south ranged from 11 to 106 ft/day. The observed ground-water velocities indicate a strong influence or predominance of conduit flow within the portion of the Hinckley aquifer evaluated in this study.

The existence of conduits in the ground-water system is indicated by the rapid ground-water flow in a direction parallel to the Hinckley Fault and by correlation among known karst features near the lagoons, the self-potential geophysical survey, and measured joint patterns in the Hinckley Sandstone. Furthermore, the pattern of dye detections, both for the Rhodamine WT and fluorescein, is inconsistent with porous-medium flow but is consistent with widely documented phenomena in fractured- and conduit-flow aquifers. However, ground-water flow is not restricted to fractures and conduits in the Askov area. The Hinckley is a permeable sandstone. Hence, flow does occur through the primary porosity, albeit at a much slower rate than through the conduits, especially where ground-water pumping may induce or increase hydraulic gradients. This combination of movement through conduits and through the porous medium creates the potential for influences of the lagoon effluent over a broader area.

4.2 Influences on the Ground-Water System

4.2.1 Possible Effects Under Normal Stream Flow

Under normal conditions, the entire flow of Bear Creek flows into the Big Sink Hole, then moves downward and becomes part of the ground-water system. Sewage lagoon effluent is normally discharged to Bear Creek upstream from the Big Sink Hole, and also enters the ground-water system.

4.2.2 Possible Effects Under High Stream Flow or Lagoon Failure

During high-flow conditions, Bear Creek overflows its banks downstream from the lagoon and floods the wetland west of the lagoons, including several sinkholes that are immediately adjacent to the lagoon. These sinkholes drain rapidly when flow conditions decrease to the point that Bear Creek becomes confined to its banks. Wetland flooding has been observed to discharge into the sinkholes adjacent to the lagoons. Some lagoon effluent discharged during high flow probably enters the ground-water system through these sinkholes. Also, because of their proximity to the lagoon, the behavior of the fluorescein dye injected into these sinkholes is the best available predictor of contaminant flow directions and velocities that would result if the lagoon should fail by partial collapse into a hypothetical new sinkhole beneath the lagoon.

4.3 Receptor Survey

The Rhodamine WT dye test was designed to trace the movement of ground water and lagoon effluent that enters the Big Sink Hole. This test identified two wells (W02 and W26), and possibly two other wells (W27 and W28), that are hydraulically connected to the Big Sink Hole that receives sewage effluent during routine operations at the lagoon. No dye was detected in three other wells farther downgradient (W33, W34, and W35). However, it is possible that dye did not appear in these latter wells because mixing reduced the concentration of dye below the detection limit. Dye might appear in these wells if the trace was repeated using a larger quantity of dye.

The fluorescein dye trace identified four wells (W06, W07, W10, and W25) and possibly one other well (W19), that are hydraulically connected to sinkholes immediately adjacent to the lagoon. One hypothesis is that dye first travels along a northeast-southwest-trending fracture and then moves laterally away from the fracture toward individual wells. Ground water moves as rapid conduit flow along the fracture and then as slower flow either along smaller joints that intersect the major fracture or as porous-medium flow. Hence, the time of travel from the point of dye injection to a particular well is controlled primarily by the distance of that well from major fractures. The dye trace may have ended too soon for dye to reach other wells that are relatively close to the lagoon, because they are farther from the major fracture (Figure 17).

The sinkholes next to the lagoon may function as both recharge and discharge features; that is, they act as surface-water sinks when the water table is low and as springs when the water table is high. This dual mode may explain the indication of fluorescein in Bear Creek (X07) during a period of both high water table and high flow and after the dye was flushed from the creek by normal flow. The fluorescein injection point, D55, acted as a sinkhole when the dye was injected, because the water table was lower and flow in Bear Creek was low. The indication of fluorescein in Bear Creek (X07) during the period of 39 to 67 days after injection correlates with both a high water table at the lagoon and a high stage at the Big Sink Hole (Figure 13). Backflow through sinkhole D55 while it was inundated with surface water during that time was the only source of fluorescein available to Bear Creek and X07.

Fecal coliform bacteria were detected in the three monitoring wells nearest the lagoon (W20, W21, W22) during a period of high stream flow and high water table. Their plate counts were comparable to those from lagoon water samples, indicating that the hydraulic conductivity of the lagoon bottom is sufficiently high to allow movement of viable bacteria from the lagoon, through the lagoon liner, and to the water table in the vicinity of the wells. The flat water table under the lagoon and lower static water level at monitoring well W23 may indicate that the lagoon forms a local mound on the water table. This interpretation is supported by ground-water elevations in residential wells near the lagoon that are significantly lower than ground-water elevations in the monitoring wells (Table 1).

4.4 Geologic Hazards

The karst landscape in the study area includes cavities and conduits in the Hinckley Sandstone that formed during a long and complex geologic history. A significant portion of the ancestral karst landscape was probably removed by glacial erosion during the past two million years. What remains of the original karst landscape has been buried by glacial material that ranges in thickness from a few feet to a few tens of feet in the study area.

Karst features found on the present landscape were created by the collapse of glacial material into existing cavities in the Hinckley Sandstone. By a process called piping, movement of ground water in the unsaturated zone carries material from the base of the glacial deposits downward into cavities in the sandstone. This results in the upward enlargement of the cavities into the glacial material. Collapse and creation of a sinkhole occurs when the overlying glacial material weakens and becomes unable to support itself. Changes in land use may redirect surface-water runoff, infiltration patterns, and unsaturated-zone flow in ways that could result in the creation of a new sinkhole. The correlation between land-use changes and appearance of new sinkholes is well documented in other karst areas. Hence, new construction in a known karst area or in proximity to existing sinkholes, such as the site of the current lagoon or some of the possible sites for a new lagoon, may cause the creation of new sinkholes.

The rate of cavity and conduit enlargement in the Hinckley Sandstone is probably much lower than the rate of movement of glacial material into preexisting sandstone cavities. The currently visible sinkholes are developed in the unconsolidated sediments over the sandstone. However, the data are not sufficient to calculate or even estimate a rate. Hence, it is not possible to estimate the probability of failure during a given time span. Sinkholes clearly occur in clusters and are typically linked to the underlying geologic formation and structure. In general, the single best predictor of where a new sinkhole will form is the prior presence of a sinkhole in the immediate vicinity.

Sinkholes already exist in the area immediately around the lagoon. The geophysical survey detected other anomalies that indicate enlarged fractures or cavities very near the lagoon. Even if the rate at which new sinkholes appear at the surface is very slow to non-existent on the time scale of a human lifetime, events that are rare by human standards do occur during our lifetimes. Well-documented cases of human-induced sinkhole development indicate that water impoundments, construction activities, and changes in surface drainage are major factors influencing sinkhole development. Although the possibility of a rapid failure of the lagoon exists, the probability of such an event cannot be quantified given our present data and understanding of the study area.

4.5 Expansion of Current Lagoon System

Expansion of the lagoon system at the present site must address the same issues that exist with the current lagoon system. First, the possibility that a new lagoon cell would collapse into a new sinkhole is comparable to that for the existing cells. Second, the amount of lagoon effluent that would enter the ground-water system at the Big Sink Hole would be increased in the event of a failure.

The presence of fecal coliform bacteria in the three monitoring wells installed through the lagoon berm indicate that the lagoon is leaking (Table 8a, 8b). This interpretation is confirmed by the water quality analyses from these wells and the lagoon, by directions of ground-water flow indicated by the dye traces (Figures 16 and 17), and by static water levels measured in the monitoring wells (Table 7, Figure 13). Lagoon leakage of effluent or effluent constituents should be remedied regardless of whether the lagoon system is expanded.

Expansion of the current lagoon system presents several issues that should be addressed:

- Increase in the volume of effluent reaching the Big Sink Hole and the wells downgradient
- Leaks in the existing lagoon liner
- Collapse of the existing lagoon into a sinkhole.

The sanitary sewer system is known to have a significant infiltration problem. The need for expansion of the existing lagoon may decrease if the sewer system is repaired. As a second alternative, the lagoon could be moved to a site south of the area (i.e., southeast of the Hinckley Fault) where karst features occur. Third, the current lagoon could be reconstructed to reduce the possibility of collapse into the karst beneath it. This would address the issue of lagoon collapse, but would not address the issue of the fate of effluent that continues to enter the ground-water system. Fourth, the lagoon system could be replaced by a more sophisticated treatment system. Treating effluent to meet drinking water standards, rather than surface-water standards, may be deemed necessary considering the relatively short time needed for flow from the Big Sink Hole to reach downgradient residential wells.

The four alternatives identified are based on the findings and relevance of the work completed under this investigation. There are certainly other alternatives that could be considered. However, further analysis of the Askov wastewater treatment system alternatives is beyond the scope of this study.

4.6 Implications for Future Work

The dye-trace tests and geophysical survey conducted by this study provided useful information that could not have been gathered in another way or as cost effectively. These study methods are useful tools that should be considered for investigations of other facilities in both sandstone and limestone karst regions of Minnesota. However, the specific application of these methods needs to be designed for the particular hydrogeologic conditions for each investigation.

A receptor survey could have been conducted by a single or several rounds of water sample collection from residences in the area followed by laboratory analysis. However, the laboratory analyses conducted for wells where dye was detected failed to find a single example of a water quality standard being exceeded. Hence, a purely chemical survey would have incorrectly concluded that there are no influences on receptor wells caused by the lagoon operation.

The aeromagnetic survey used by the Minnesota Geological Survey to prepare the Pine County geologic and hydrologic atlases indicates that the method is a potentially promising geophysical tool for further assessment of karst developed in the Hinckley Sandstone. A finer-resolution survey would likely yield more localized anomalies indicative of karst conditions. Other remote sensing methods should also be evaluated for carrying out more detailed assessments. An investment in background surveys such as these would likely be very useful in providing detailed context for future investigations of other permitted facilities in the region.

Whereas these methods can refine the horizontal control of structurally related karst features, little is yet known on whether specific sub-units of the Hinckley are particularly susceptible to solution processes that could lead to formation failure or collapse. The presence of sinkholes west of the Hinckley Fault, where the middle portion of the Hinckley Sandstone is subcropping, and the absence of sinkholes east of the Hinckley Fault, where the bottom portion of the Hinckley Sandstone is present, gives only a rough indication of how vertical variations in the stratigraphy of the Hinckley Sandstone control the development of karst features. The stratigraphic variations that control karst development may be observable within caves along the Kettle River. Systematic application of downhole gamma logging and flowmeter logging in existing wells would provide useful information for identifying the vertical controls on karst development that exist within the local and regional stratigraphy.

Chloride-to-bromide ratios reflect the source of ground-water recharge. In natural ground waters that are suitable for domestic use, the concentrations of both chloride and bromide are very low compared to the detection limits of traditional laboratory equipment. Recent improvements in ion chromatographic detection limits of bromide ions result in an economical, rapid tool that can help identify ground-water recharge to residential wells. Initial analyses of several wells in the Askov area indicate that this technique could provide useful information on the source(s) of recharge to individual wells.

Finally, it should be noted that conduit flow is a significant part of the ground-water system in the Askov area. Specific conduits may cause flow directions to be contrary to regional flow directions and can be radically reversed during periods of rainfall or flood events. This necessitates extra care and vigilance in the placement and monitoring of waste management or disposal systems of all types. It also mandates open and critical analysis of monitoring data, especially during periods of aquifer stress caused by pumping and adverse climatic conditions.

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Figures

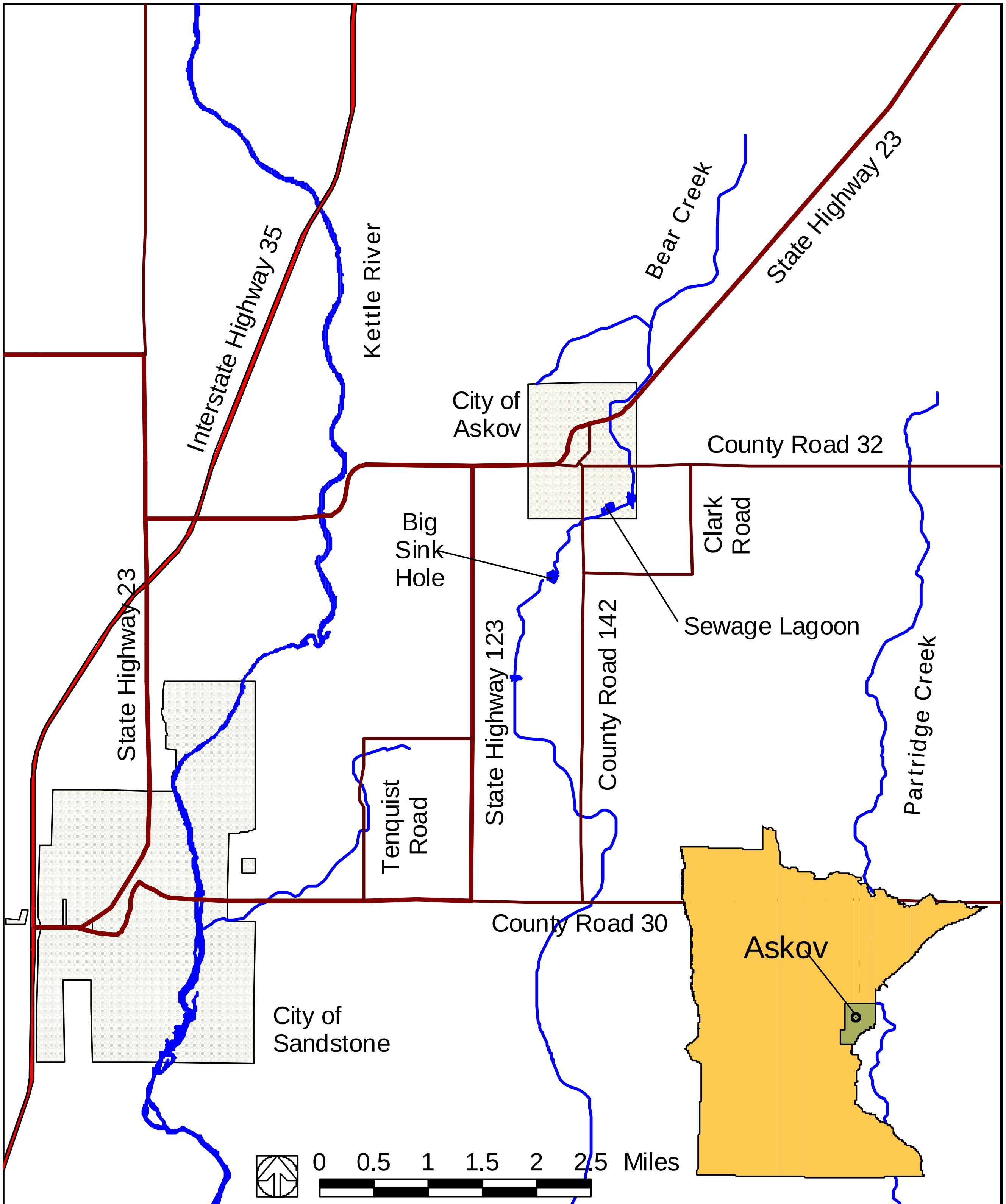

Figure 1. City of Askov and surrounding area. Inset shows the location of Pine County and Askov.

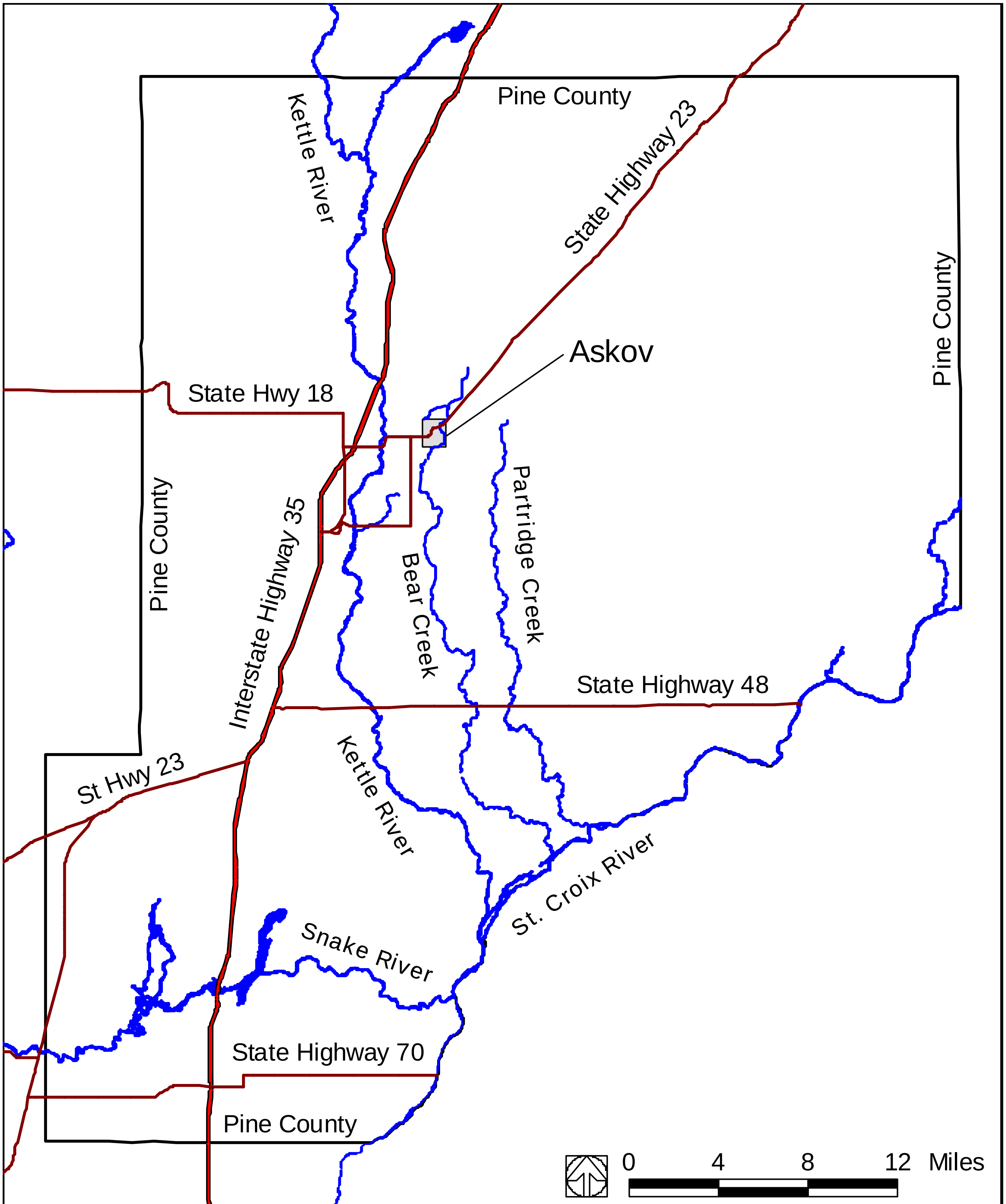

Figure 2. Rivers and creeks in Pine County

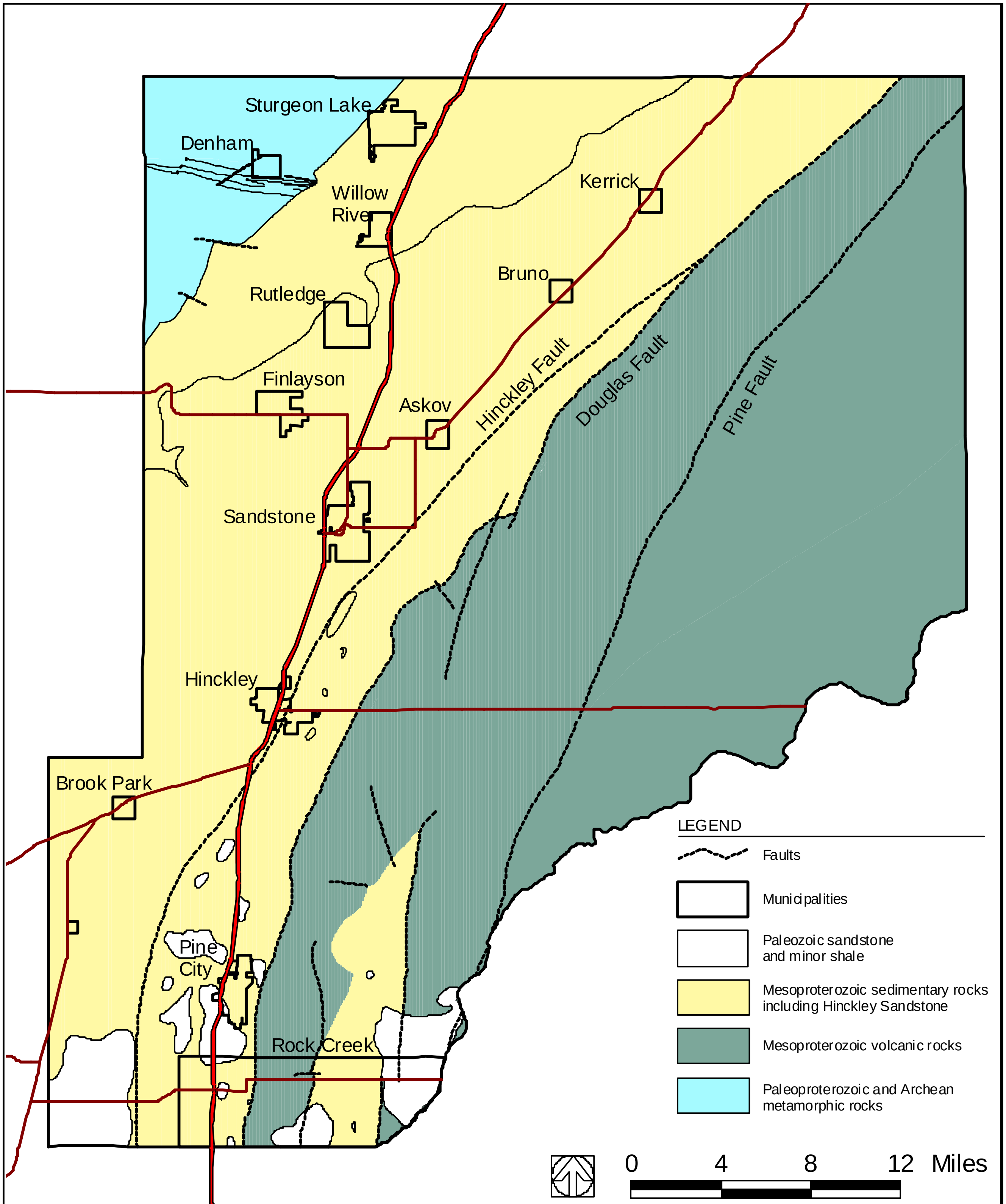

Figure 3. Generalized geologic map of Pine County (after Boerboom, 2001, 2002).

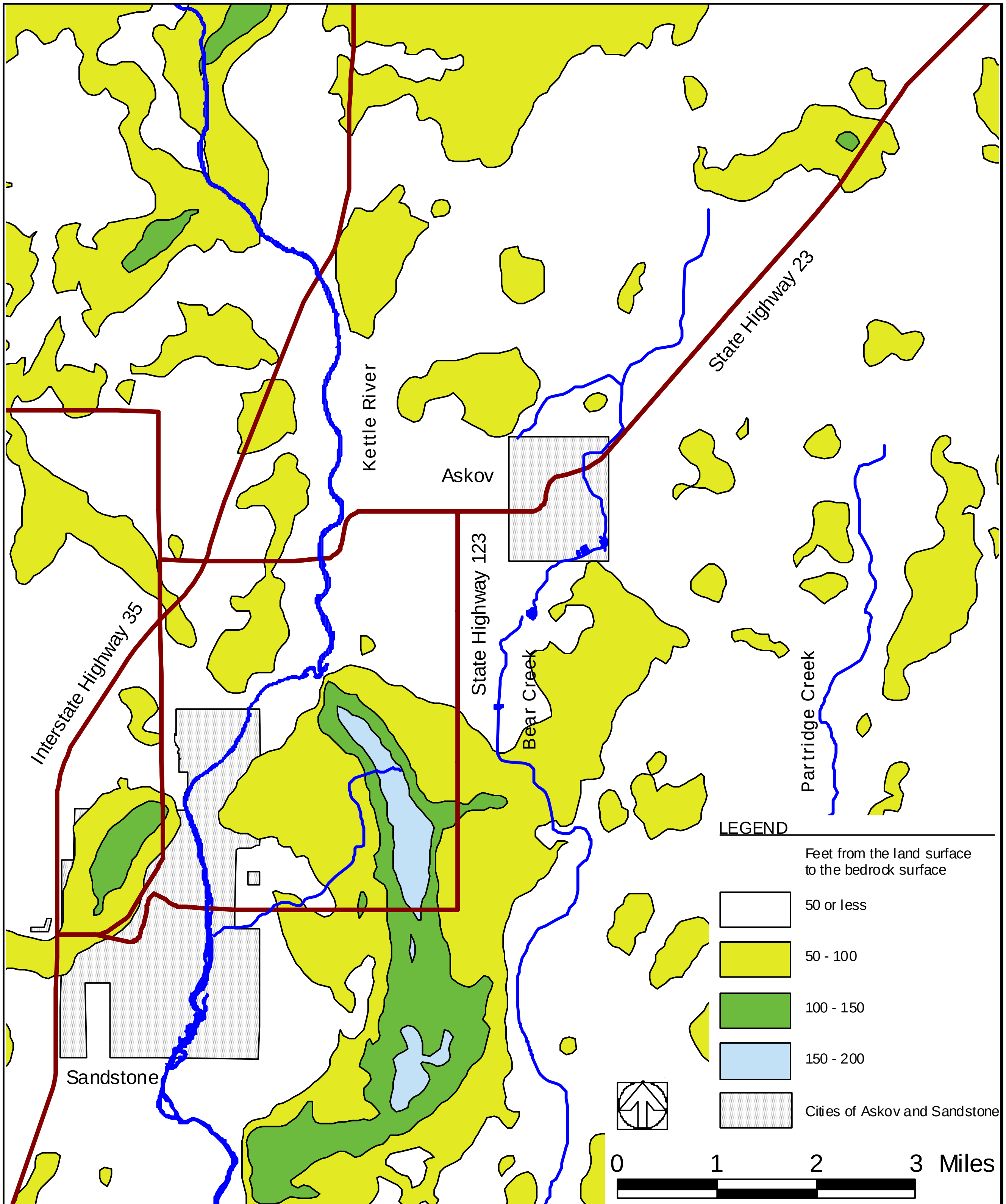

Figure 4: Depth to bedrock in the Askov area (after Setterholm, 2001).

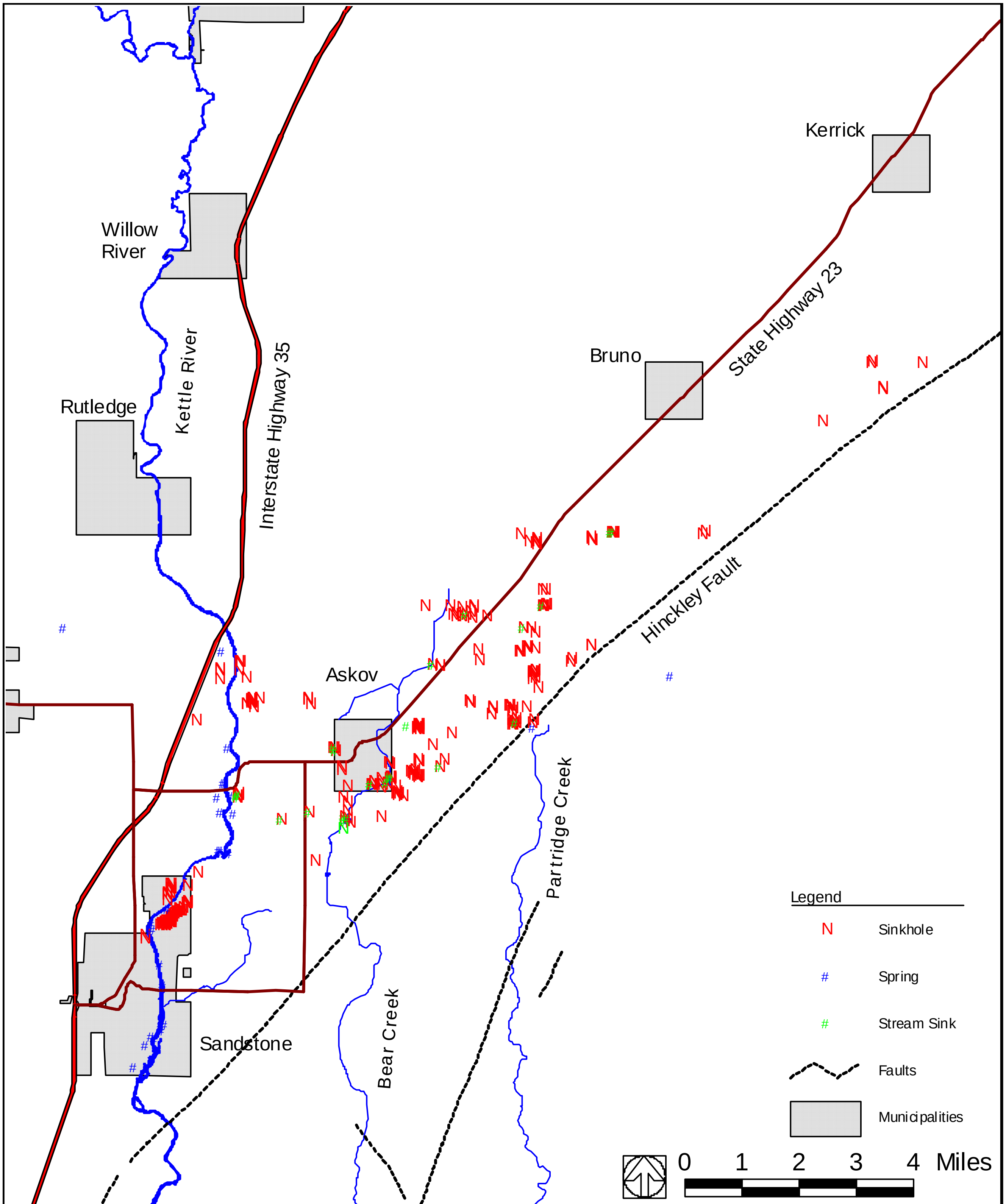

Figure 5. Sinkholes in Pine County (after Shade, et al, 2001).

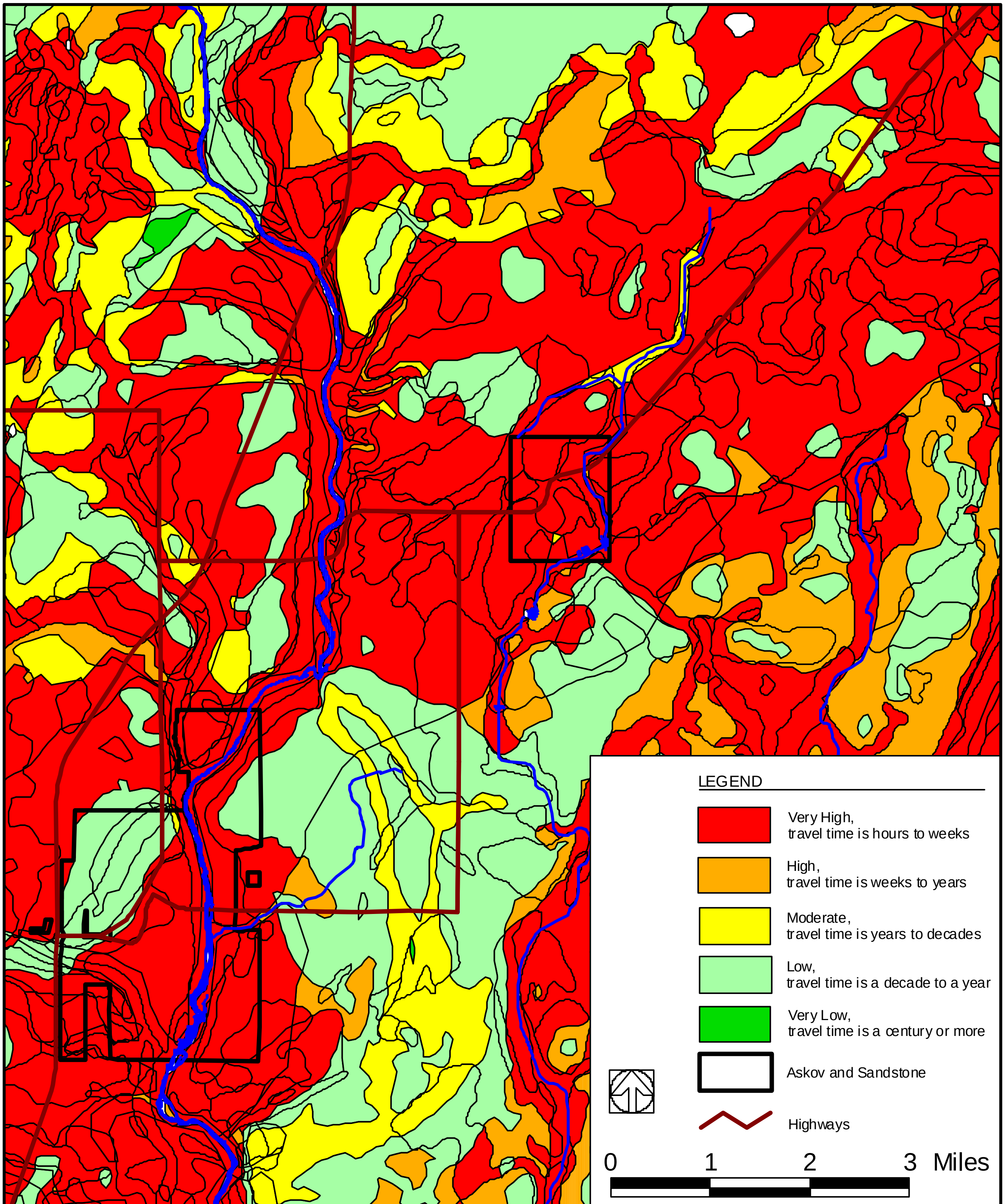

Figure 6: Sensitivity to pollution of the uppermost bedrock aquifer in the Askov area (after Berg, 2004).

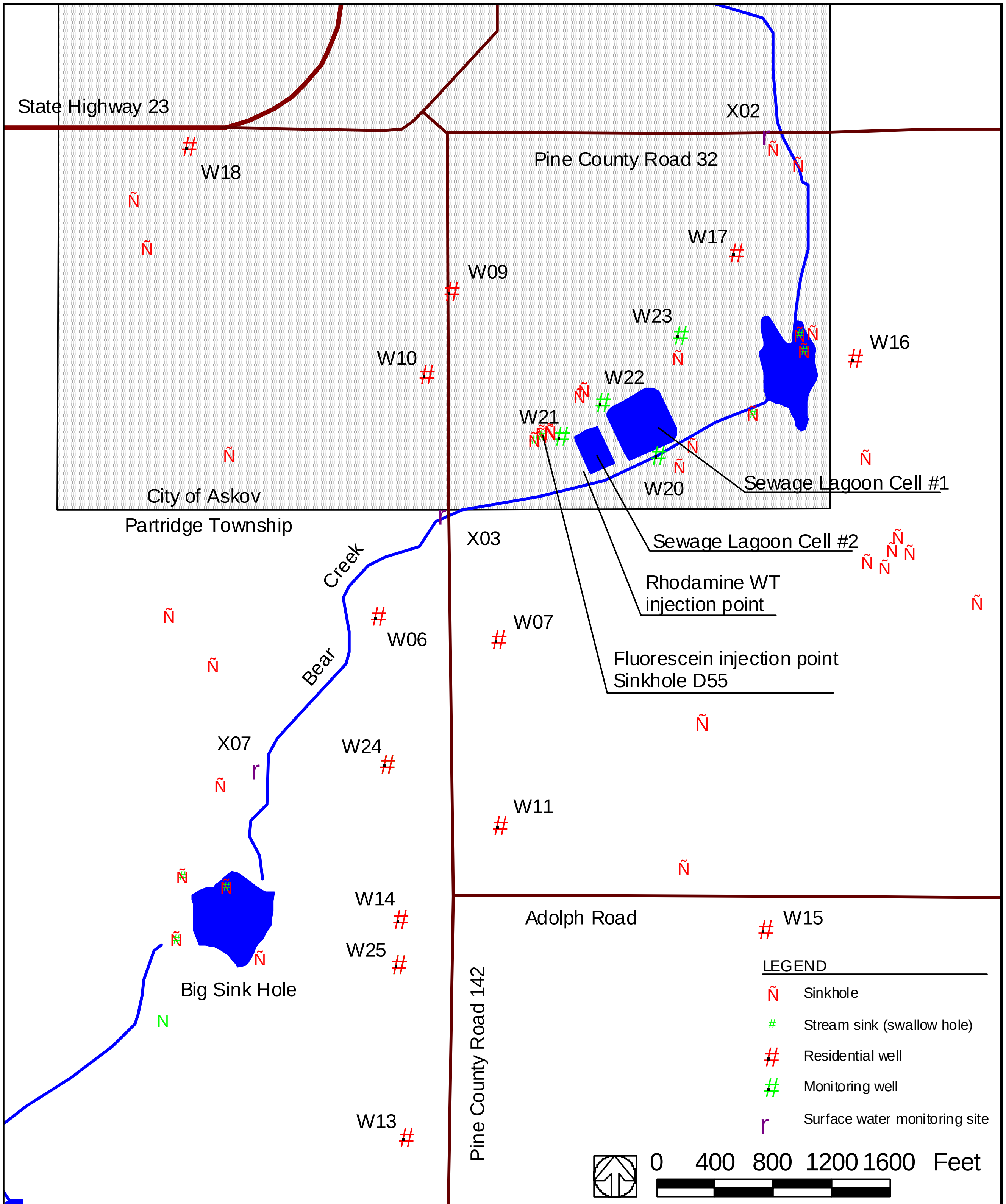

Figure 7: Locations of monitoring wells and dye injection points, 23 April 2004.

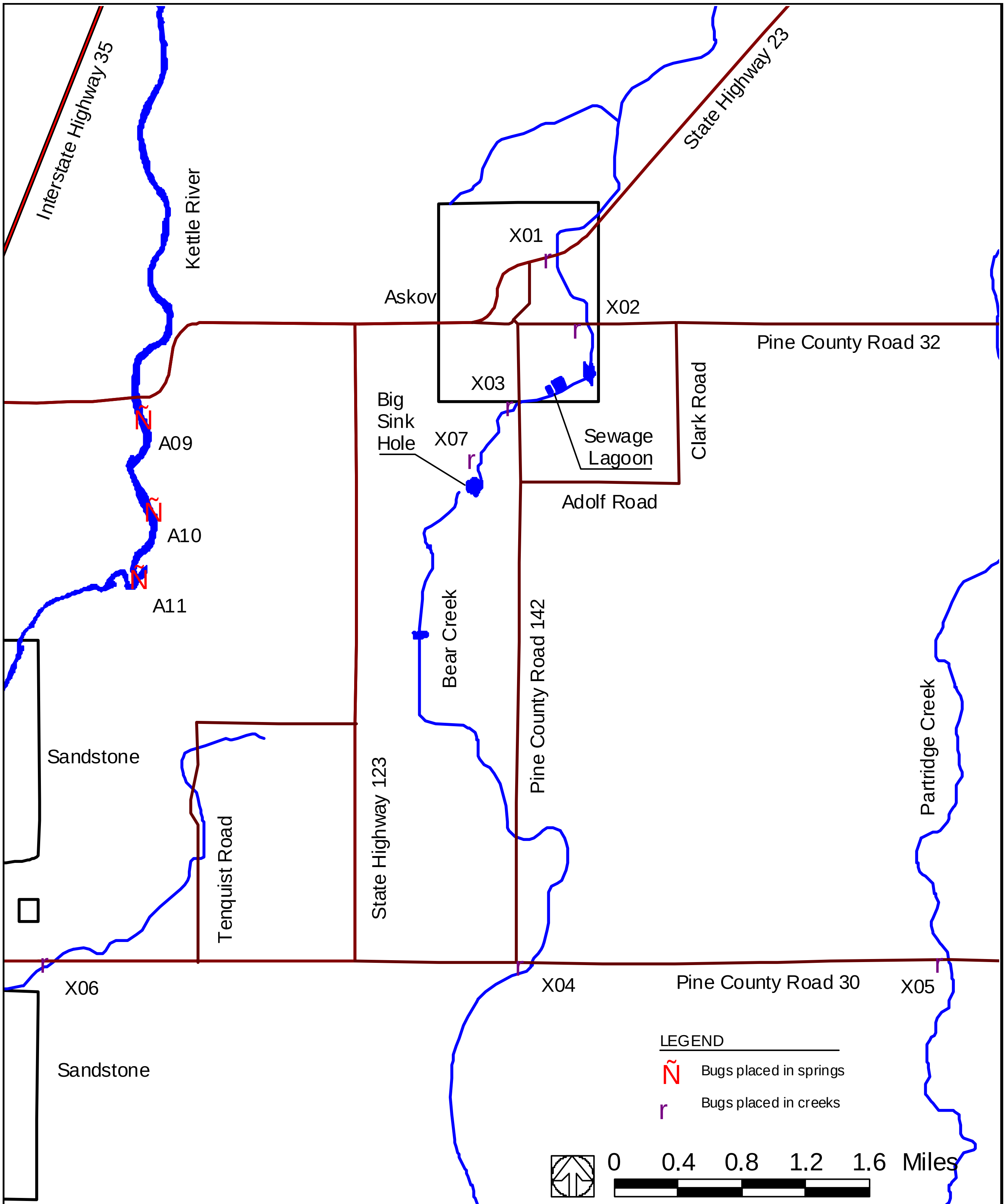

Figure 8: Charcoal detectors ("bugs") placed in surface water, 14-15 April 2004.

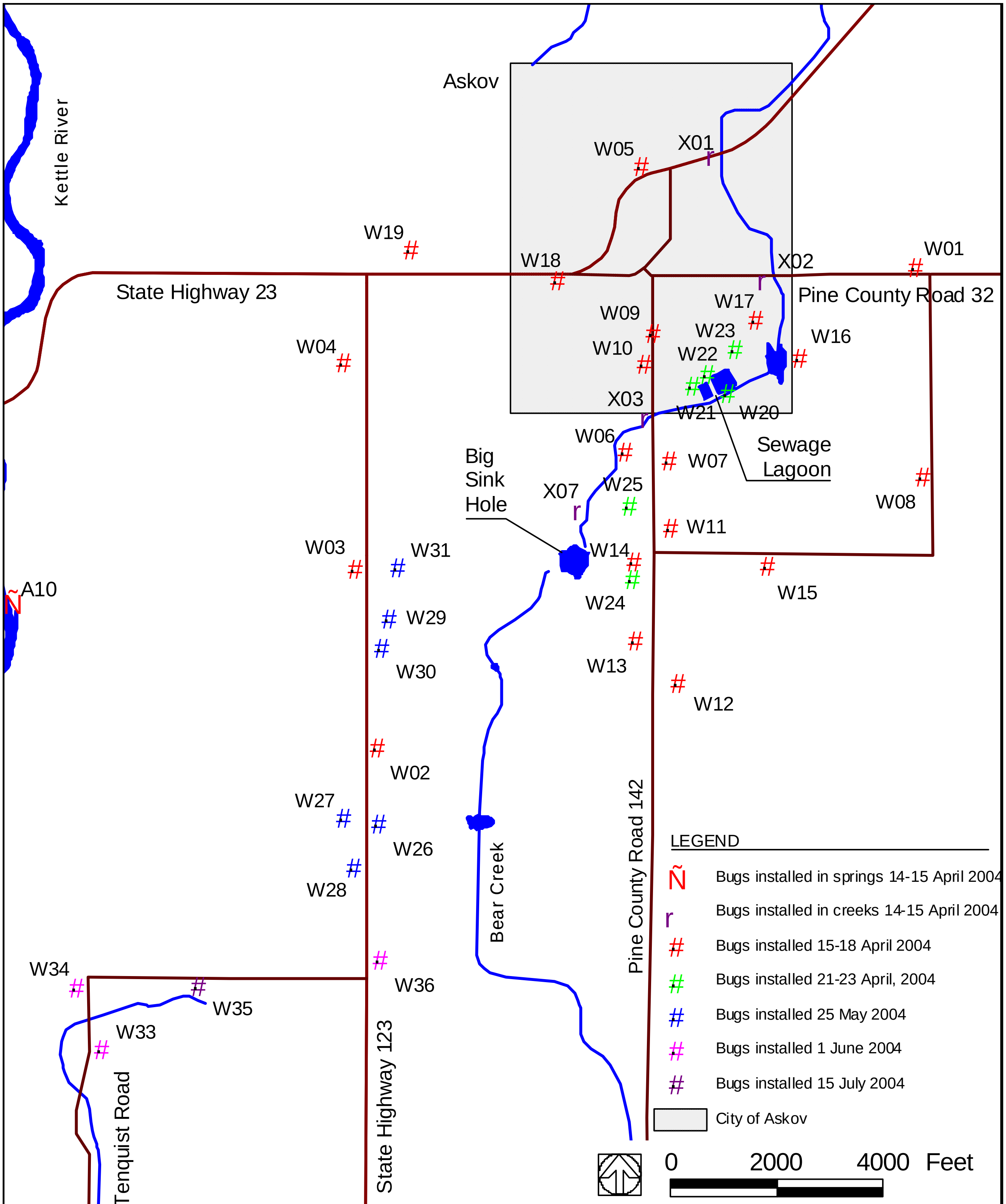

Figure 9: Charcoal detectors ("bugs") placed in residential water systems, 14-15 April - 15 July 2004.

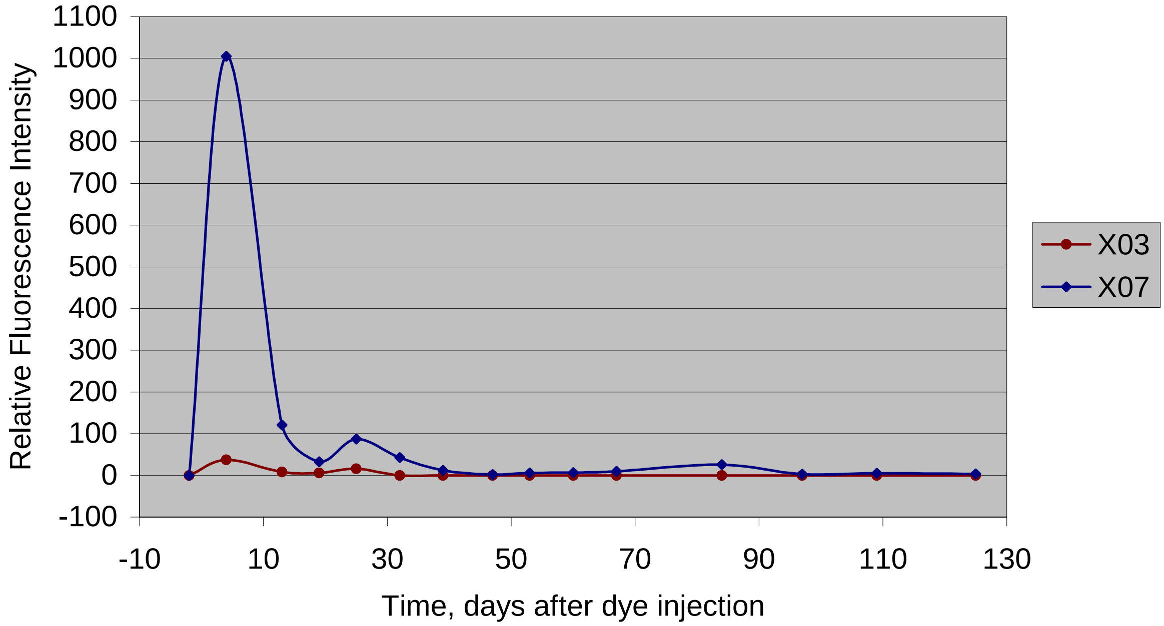

Figure 10: Break-through curves for Rhodamine WT dye detection in Bear Creek at the crossing of Pine County Road 142 (X03) and near the Big Sink Hole (X07).

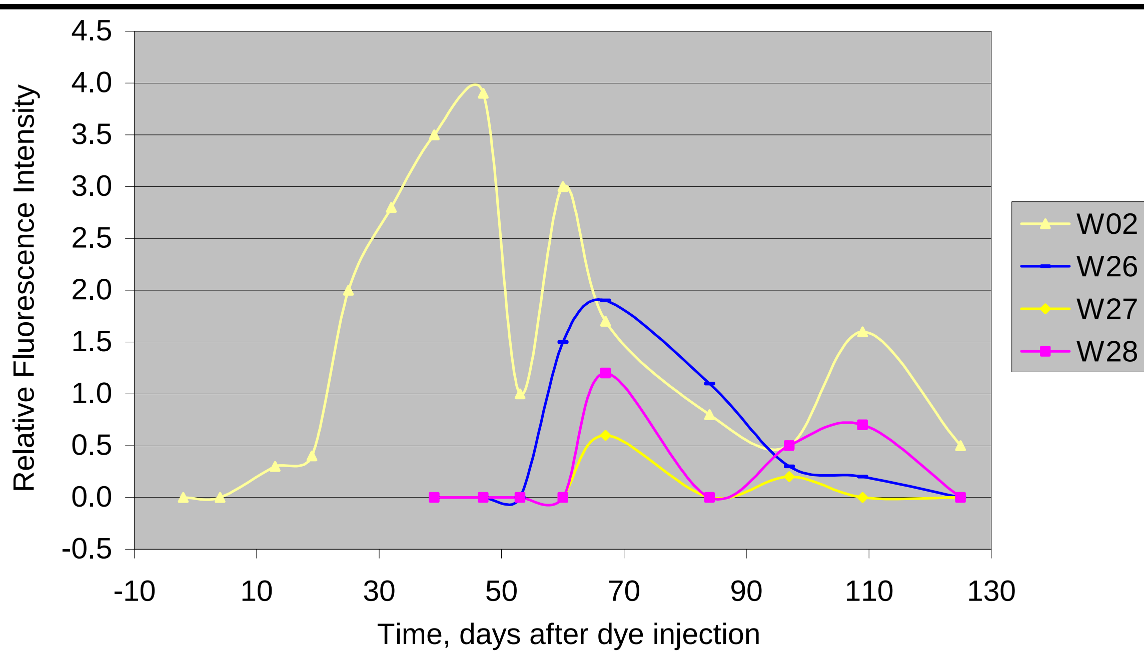

Figure 11: Break-through curves for Rhodamine WT dye detections and indications in residential wells (W02, W26, W27, W28). Note the change by a factor of 600 between the vertical scales of Figures 14 and 15.

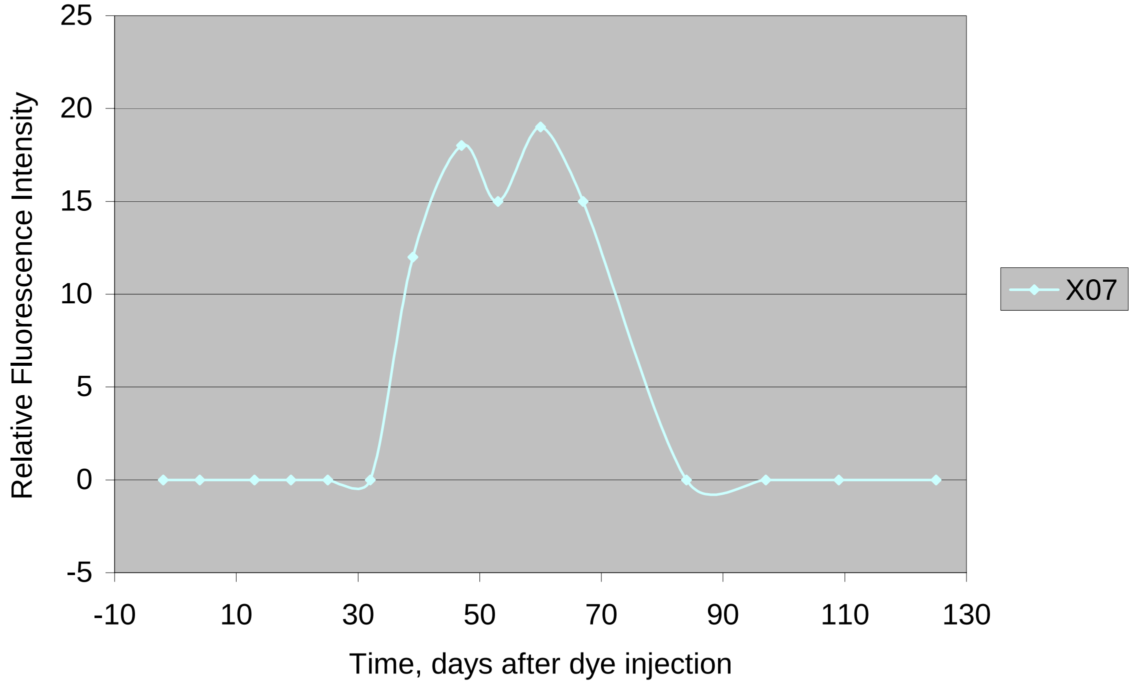

Figure 12a: Break-through curve for fluorescein dye indications in Bear Creek near the Big Sink Hole (X07).

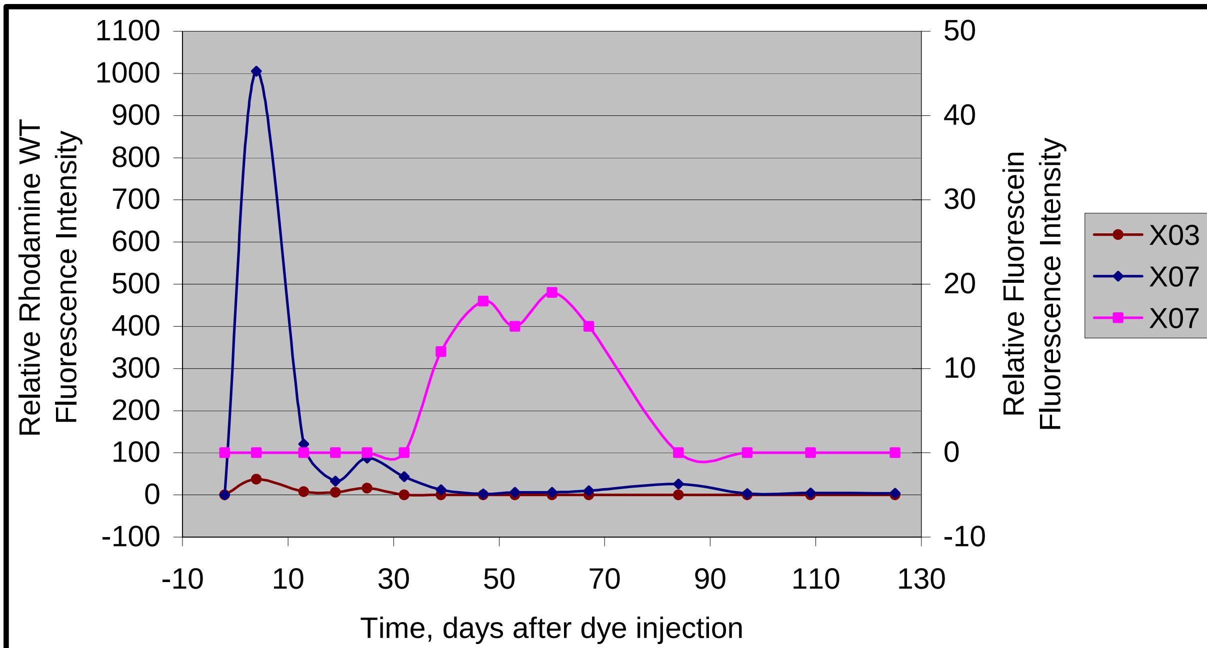

Figure 12b: Break-through curves for fluorescein and Rhodamine WT dye detections and indications in Bear Creek. Note the change by a factor of 20 between the left and right vertical scales.

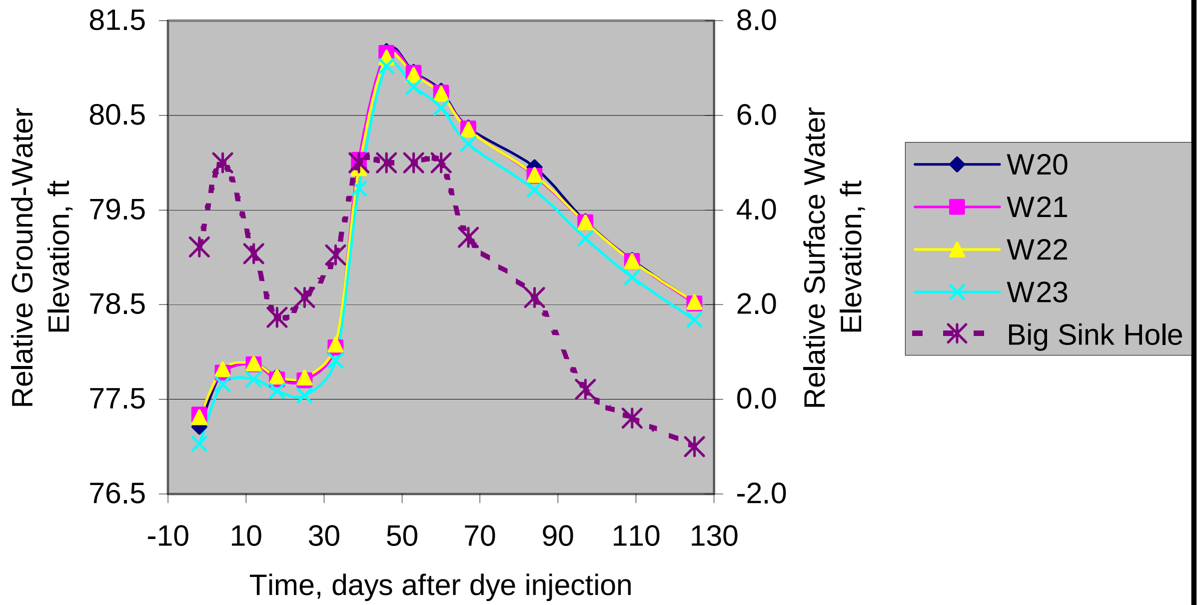

Figure 13: Relative ground-water elevations in monitoring wells and relative surface water elevation in the Big Sink Hole. Measurements of >4 ft taken when the staff gauge at the Big Sink Hole was submerged are plotted as 5 ft.

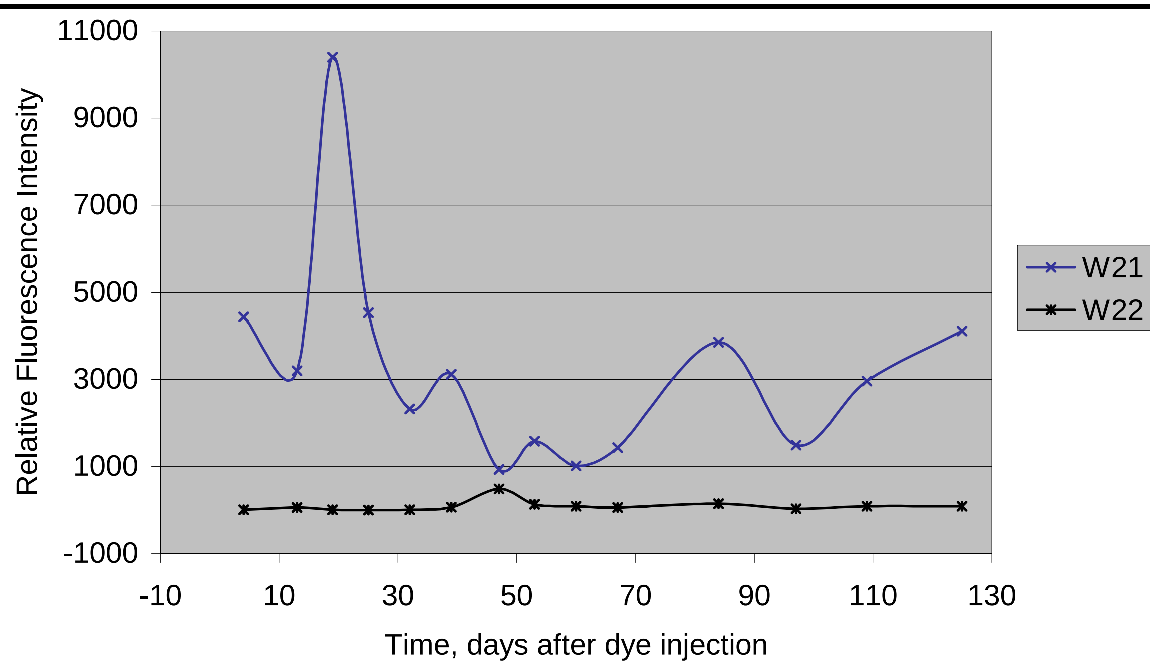

Figure 14a: Break-through curves for fluorescein dye detection in lagoon monitoring wells (W21, W22). Note that the vertical scale is from -1000 to +11,000.

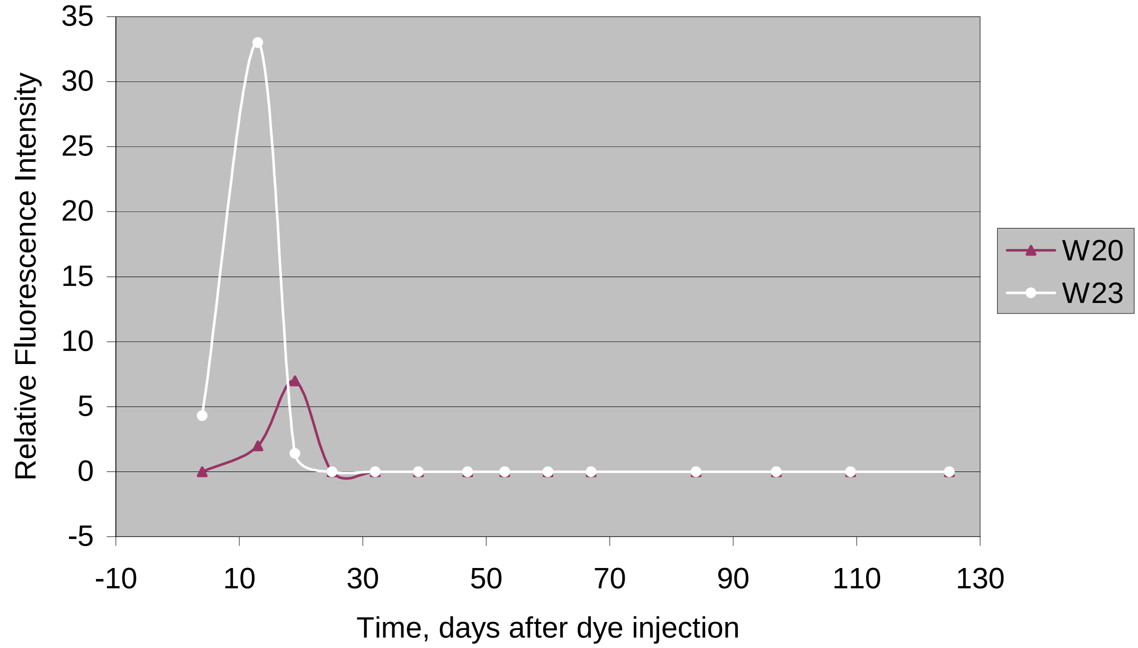

Figure 14b: Break-through curves for fluorescein dye detections and indications in lagoon monitoring wells (W20, W23). Note that vertical scale is from -5 to +35.

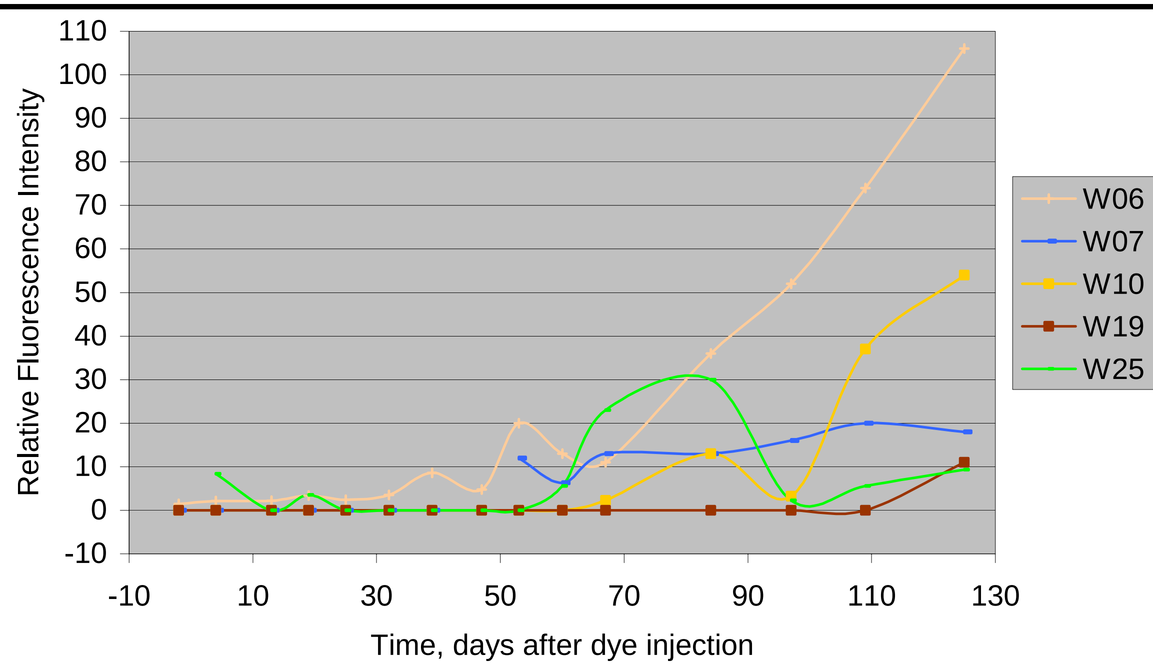

Figure 15: Break-through curves for fluorescein dye detections and indications in residential wells (W06, W07, W10, W19, W25). Note that the vertical scale is from -10 to +110.

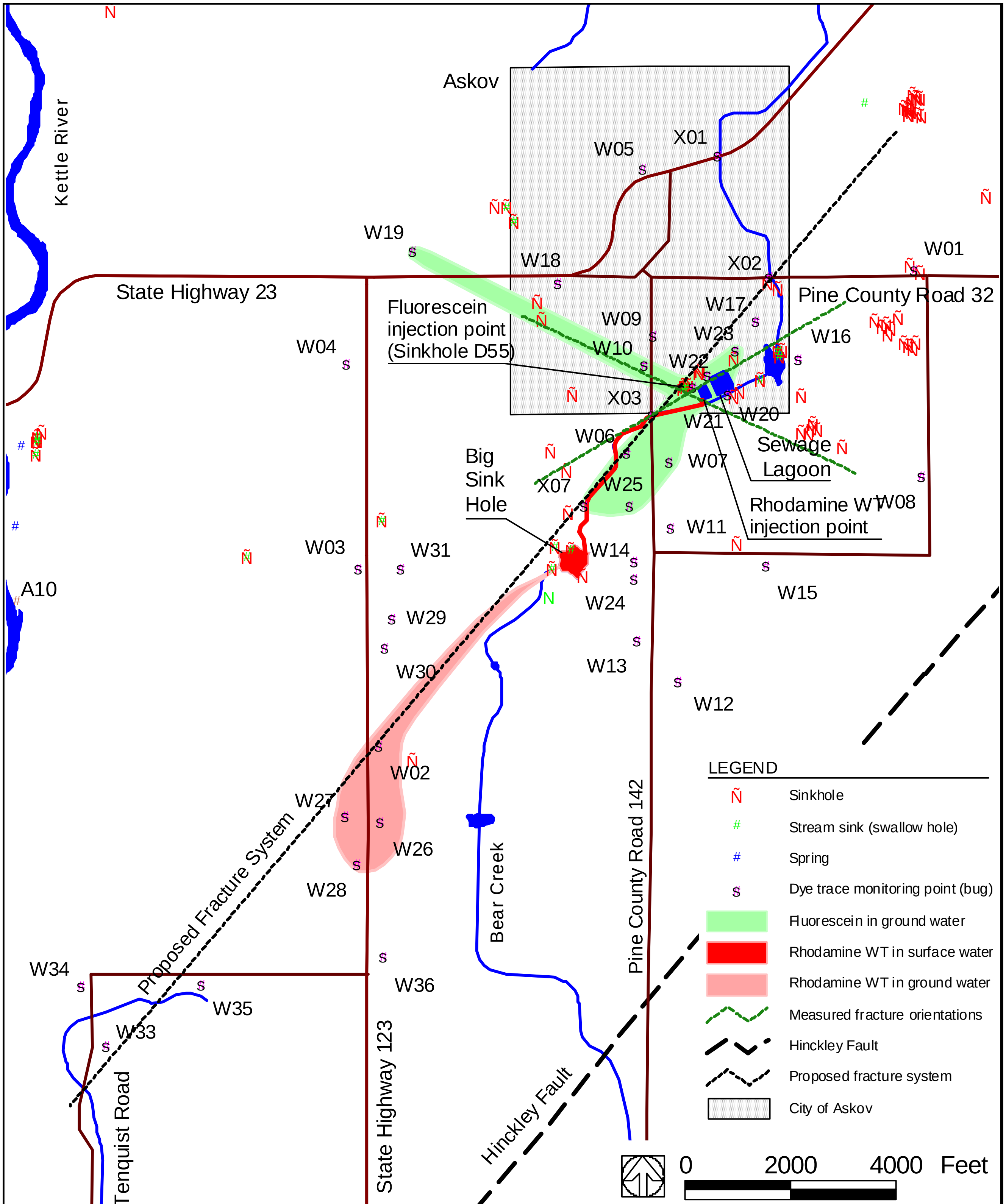

Figure 16: Relationship of karst features, dye detection, and structural trend of the Hinckley Fault. The proposed fracture system is drawn through W02 and parallel to the Hinckley Fault. The two principal fracture orientations measured by Boerboom (2002) are drawn through the fluorescein injection point.

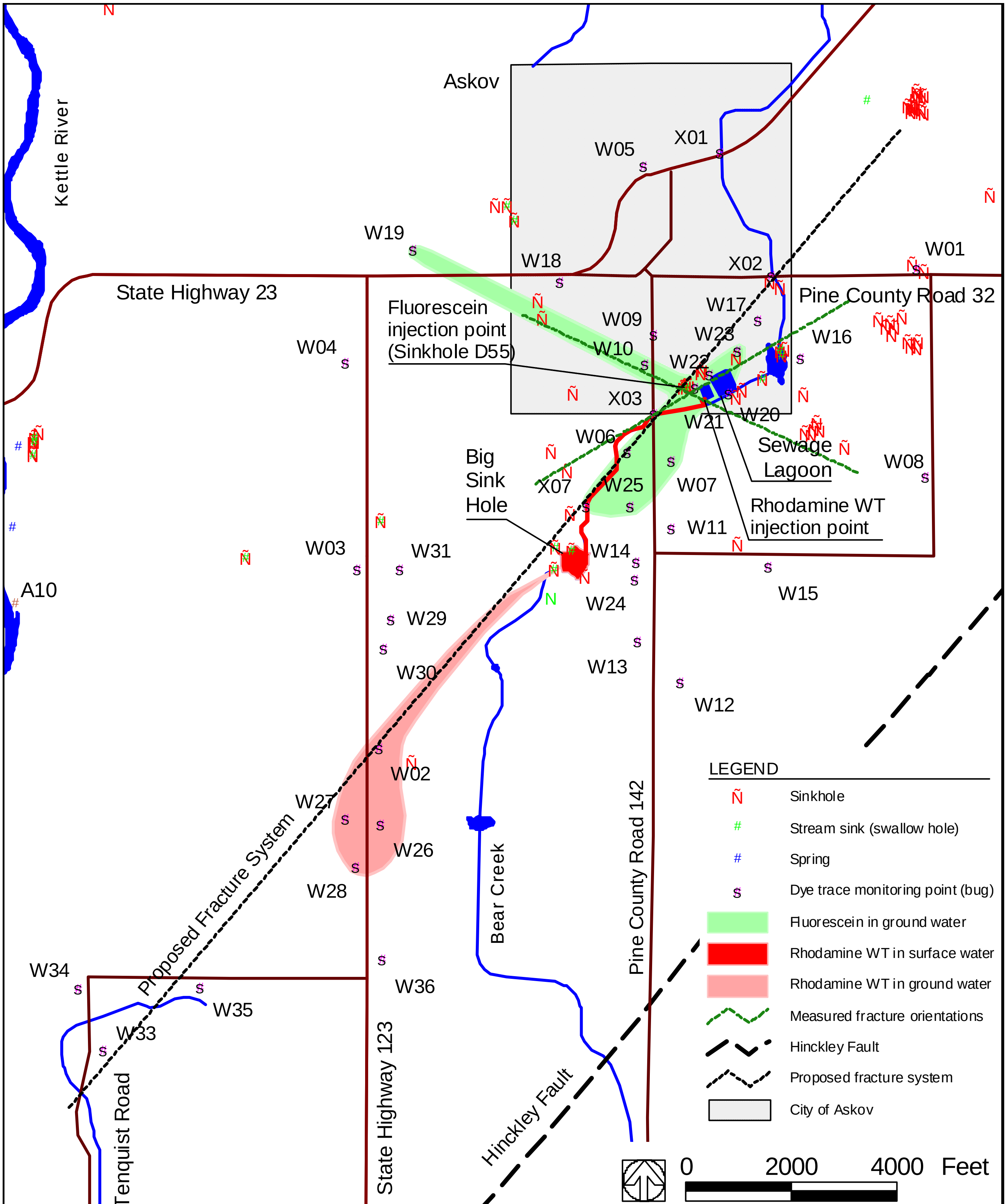

Figure 17: Movement of Rhodamine WT and fluorescein dyes. Rhodamine WT reached the Big Sink Hole in 3 hrs and was detected in W02 and W26 25 and 60 days later, repectively. After dye injection, fluorescein was detected in the 4 monitoring wells northeast of the injection point in less than 4 days; it was detected in W06, W07, and W25, southwest of the injection point, 19, 84, and 67 days, respectively, and in W10 and W19, northwest of the injection point, 67 and 125 days, respectively.

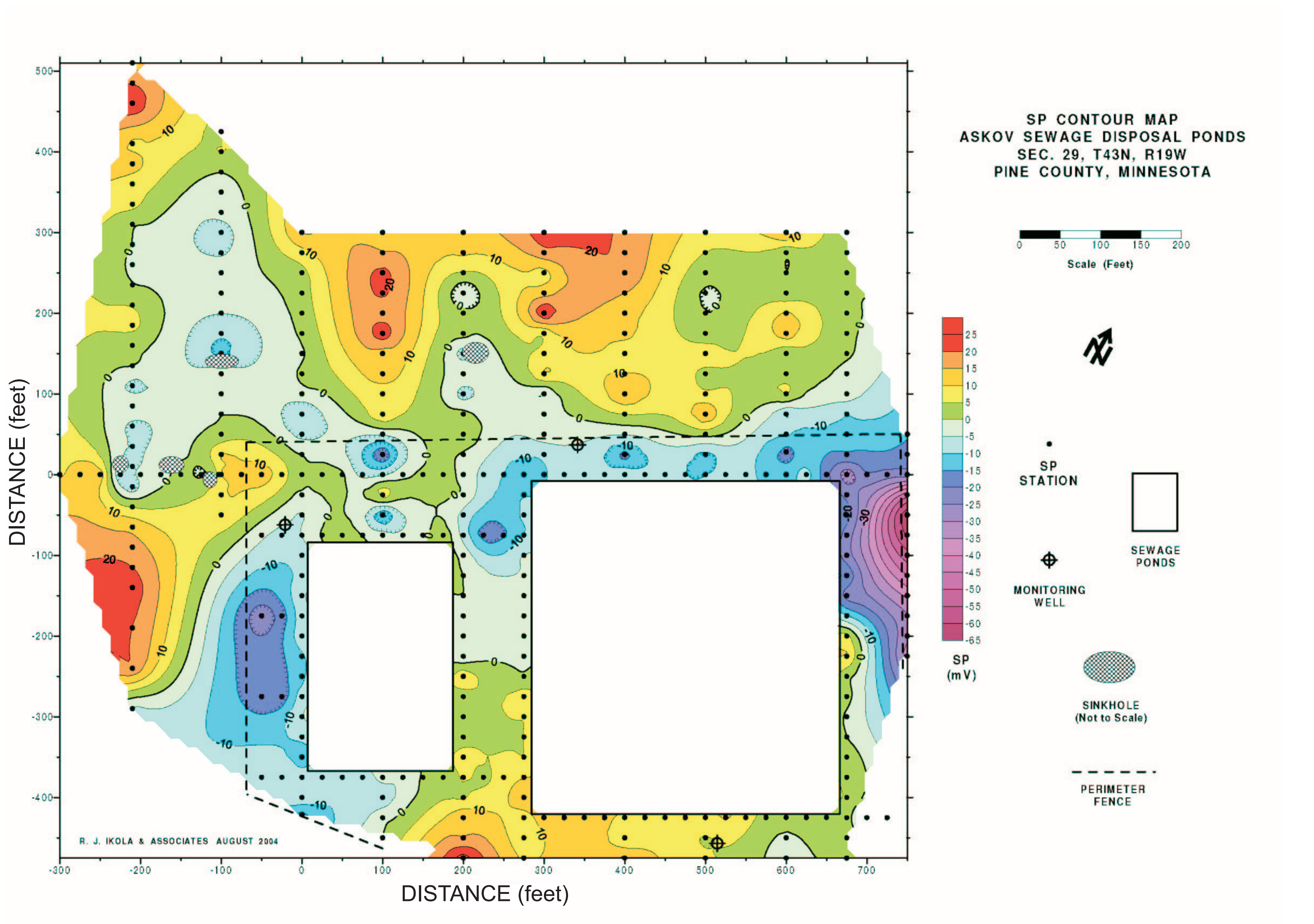

Figure 18. Self-potential contour map, Askov sewage disposal ponds (Ikola 2004b)

2699 SP Contour Map.fh11 10/08/04 CO

Tables

Table 1. Selected data for some wells used for the dye traces from the County Well Index

Bug ID	Unique No.	Total Depth (ft)	Elevation (ft)	Depth to Bedrock (ft)	Depth of Casing (ft)	SWL (ft)	Ground-Water Elevation (ft)
W01	449381,2	200	1178	23	115	--	--
W03	191242	140	1140	--	71	70	1070
W06	142945	95	1138	45	74	48	1090
W07	581953	90	1141	29	61	18	1123
W08	131783	80	1129	19	45	30	1099
W09[a]	131789	110	1152	45	70	46	1106
W10	623811	80	1151	56	60	46	1105
W11	142914	100	1160	55	78	46	1114
W12	172469	125	1145	54	68	66	1079
W14	594455	94	1160	60	63	50	1110
W19	599001	123	1165	37	40	60	1105
W20	703412	45	1145	22.5	22	23.55	1121.45
W21	703411	45	1145	25	11	21.86	1123.14
W22	703410	45	1145	28	23	23.35	1121.65
W23	703413	45	1145	22.5	21.5	23.13	1121.87
W30	192634	125	1137	34	69	62	1075
W33[a]	142998	125	1111	76	86	69	1042
W34	567556	110	1109	73	83	71	1038

[a] Data are from the log of an older well on the property that indicates a valid depth to bedrock and static water level; this study used a newer well.

Table 2. Lagoon monitoring well data

Unique No.	Bug ID	Date Drilled	Total Depth (ft)	Screened Interval (ft)	Depth to Water (ft)	Meas Pt Elev (relative ft)	Easting (UTM)	Northing (UTM)
703410	W22	4/23/04	45	23–43	23.35	104.27	517131	5114249
703411	W21	4/23/04	45	11–31	21.86	101.83	517046	5114177
703412	W20	4/23/04	45	22–42	23.55	104.08	517246	5114138
703413	W23	4/23/04	45	16–36	23.13	103.79	517293	5114389

Table 3. Charcoal detectors ("bugs") used for the dye traces

UTMe	UTMn	Bug ID	Owner	Address	Installed
513020	5113868	A09	No Charge Springx		4/15/04
513131	5112933	A10	Midway Spring		4/15/04
512988	5112242	A11	Grey Beaver Spring		4/15/04
517189	5115526	X01	Bear Creek at MN 23		4/14/04
517487	5114815	X02	Bear Creek at Pine Co 32		4/14/04
516808	5114020	X03	Bear Creek at Pine Co 142		4/14/04
516909	5108361	X04	Bear Creek at Pine Co 30		4/14/04
521149	5108395	X05	Partridge Creek at Pine Co 30		4/14/04
512104	5108397	X06	unnamed creek at of Pine Co 30		4/14/04
516419	5113488	X07	Bear Cr @ Big Sink Hole		4/16/04
518324	5114860	W01	City of Askov	6369 Kobmagergade	4/15/04
515228	5112099	W02	Robert Sahlen, Sr	59632 N St Hwy 123	4/16/04
515107	5113127	W03	Robert & Margie Dubois	60859 N St Hwy 123	4/16/04
515040	5114317	W04	Gene Krogh	62377 N St Hwy 123	4/16/04
516753	5115448	W05	Dennis Morrison	3493 Marsh Road	4/16/04
516660	5113799	W06	Paul & Martys Olesen	61715 Beaver Tail Rd	4/16/04
516913	5113751	W07	Ken & Myrna Nelson	61716 Beaver Tail Rd	4/16/04
518373	5113661	W08	Chuck Moon	61597 Clark Rd	4/16/04
516814	5114480	W09	Todd & Marta Hultman	6254 Co Rd 142	4/16/04
516764	5114307	W10	David Woehn	6225 Co Rd 142	4/16/04
516916	5113361	W11	Willard & Lorraine Rote	61182 Beaver Tail Rd	4/16/04
516963	5112471	W12	Timothy Tabor	60054 Beaver Tail Rd	4/16/04
516719	5112708	W13	Marguerite Walz	60357 Beaver Tail Rd	4/17/04
516707	5113166	W14	Richard Thomsen	60993 Beaver Tail Rd	4/17/04
517472	5113144	W15	Roger & Cynthia Jensen	35818 Adolf Rd	4/17/04
517658	5114340	W16	Ellen Lundberg	6240 Prairie Ln	4/17/04
517408	5114561	W17	Rocky Kroon	3566 Co Rd 32	4/17/04
516267	5114785	W18	Dan Battaglia	3442 St Hwy 23	4/17/04
515423	5114968	W19	Dennis Sostak	63163 St Hwy 23	4/17/04
517246	5114138	W20	703412	Lagoon area	4/21/04
517046	5114177	W21	703411	Lagoon area	4/21/04
517131	5114249	W22	703410	Lagoon area	4/21/04
517293	5114389	W23	703413	Lagoon area	4/21/04
516703	5113069	W24	Loretta Bauerfeld	60793 Beaver Tail Rd	4/21/04
516680	5113489	W25	Paul & Carole Maloney	61395 Beaver Tail Rd	4/23/04
515239	5111654	W26	Steve & Laurie Loew	59094 N St Hwy 123	5/25/04
515035	5111693	W27	Brandon & Lee Anne Gibson	59095 N St Hwy 123	5/25/04
515098	5111407	W28	Marie Randolph	58781 N St Hwy 123	5/25/04
515300	5112842	W29	Tessa Anderson	6068 N St Hwy 123	5/25/04
515259	5112670	W30	Rob & Donna Sahlen	60362 N St Hwy 123	5/25/04
515352	5113130	W31	Doug & Tara Casey	60696 N St Hwy 123	5/25/04
513644	5110355	W33	Margaret Tenquist	57470 Tenquist Rd	6/1/04
513500	5110710	W34	Alton & Pauline Gullingsrud	57917 Tenquist Rd	6/1/04
514203	5110719	W35	Julianna Beavens	31832 Tenquist Rd	7/15/04
515249	5110877	W36	Everett & Evelyn Korpi	58130 N St Hwy 123	6/1/04

Table 4. Sampling sites for water quality analysis

ID	Sample Date	Sample Time	Comments
W02	5/28/04	12:27	Purged for 15 minutes. Collected at hydrant.
W02	7/7/04	13:45	Purged for 14 minutes. Collected at hydrant.
W06	7/9/04	11:50	Purged for 11 minutes. Collected at hydrant.
W25	7/9/04	11:31	Purged for 10 minutes. Collected at spigot on west side of house.
W26	7/9/04	11:06	Purged for 11 minutes. Collected at spigot on front of house.
W27			Not sampled: No one was home and water was inaccessible.
W28	7/9/04	10:35	Purged for 10 minutes. Collected at spigot on north side of house.
W10	7/9/04	12:11	Purged for 15 minutes. Collected at hydrant.

Table 5a. Results from the Rhodamine WT dye trace
(Smaller, italicized numbers represent indications of dye. Larger, solid numbers represent confirmed detections of dye.)

Date	4/21/04	4/27/04	5/6/04	5/12/04	5/18/04	5/25/04	6/1/04	6/9/04	6/15/04	6/22/04	6/29/04	7/16/04	7/29/04	8/10/04	8/26/04
Days[a]	–2[b]	4	13	19	25	32	39	47	53	60	67	84	97	109	125
Spring Samples															
A09	--	--	--	--	--	--		--	--	--	--	--	--	--	--
A10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
A11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Creek Samples															
X01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X02	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X03	--	37	8	6	16	--	--	--	--	--	--	--	--	--	--
X04	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X05	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X06	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X07	--	1005	121	33	87	43	12.1	*2.2*	*6*	*6.4*	10	26	2.8	5	3.7
Residential Well Samples															
W01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W02	--	--	*0.3*	*0.4*	2	2.8	3.5	3.9	1	3	1.7	0.8	0.5	1.6	0.5
W03	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W04	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W05	--	--	--	--	--		--	--	--	--	--	--	--	--	--
W06	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W07	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W08	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W09	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W13	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W14	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W15	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W16	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W17	--	--	--	--	--	--	--	--	--	--	--	--	--	--	
W18	--	--	--	--	--	--	--	--	--	--	--	--		--	--
W19	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W24		--	--	--	--	--	--	--	--	--	--	--	--	--	--
W25		--	--	--	--	--	--	--	--	--	--	--	--	--	--
W26							--	--	--	1.5	1.9	1.1	*0.3*	*0.2*	--
W27							--	--	--	--	*0.6*	--	*0.2*	--	--
W28							--	--	--	--	1.2	--	*0.5*	*0.7*	--
W29							--	--	--	--	--	--	--	--	--
W30							--	--	--	--	--	--	--	--	--
W31							--	--	--	--	--	--	--	--	--
W33								--	--	--	--	--	--	--	--
W34								--	--	--	--	--	--	--	--
W35													--	--	--
W36								--	--	--	--	--	--	--	--
Lagoon Monitoring Well Samples							--	--	--	--	--	--	--	--	--
W20		--	--	--	--	--	--	--	--	--	--	--	--	--	--
W21		--	--	--	--	--	--	--	--	--	--	--	--	--	--
W22		--	--	--	--	--	--	--	--	--	--	--	--	--	--
W23		--	--	--	--	--	--	--	--	--	--	--	--	--	--

[a] Days after dye injection
[b] Background samples taken two days prior to dye injection

-- indicates non-detect
Blank indicates no sample

Table 5b. Results from the fluorescein dye trace
(Smaller, talicized numbers represent indications of dye. Larger, solid numbers represent confirmed detections of dye.)

Date	4/21/04	4/27/04	5/6/04	5/12/04	5/18/04	5/25/04	6/1/04	6/9/04	6/15/04	6/22/04	6/29/04	7/16/04	7/29/04	8/10/04	8/26/04
Days[a]	-2[b]	4	13	19	25	32	39	47	53	60	67	84	97	109	125
Spring Samples															
A09	--	--	--	--	--	--		--	--	--	--	--	--	--	--
A10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
A11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Creek Samples															
X01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X02	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X03	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X04	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X05	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X06	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
X07	--	--	--	--	--	--	*12*	*18*	*15*	*19*	*15*	--	--	--	--
Residential Well Samples															
W01	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W02	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W03	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W04	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W05	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W06	*1.5*[c]	*2.1*	*2.2*	3.4	*2.4*	3.5	8.6	4.8	20	13	11	36	52	74	106
W07	--	--	--	--	--	--	--		*12*	*6.3*	*13*	13	16	20	18
W08	--	8.6	--	--	--	--	--	--	--	--	--	--	--	--	--
W09	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W10	--	--	--	--	--	--	--	--	--	--	*2.3*	13	*3.2*	37	54
W11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W13	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W14	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W15	8.3[c]	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W16	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
W17	--	--	--	--	--	--	--	--	--	--	--	--	--	--	
W18	--	--	--	--	--	--	--	--	--	--		--	--	--	
W19	--	--	--	--	--	--	--	--	--	--	--	--	--	--	11
W20		--	*2*	7	--	--	--	--	--	--	--	--	--	--	
W25		8.4	--nd	3.5	--	--	--	--	--	*5.6*	23	30	2.3	5.6	9.3
W26							--	--	--	--	--	--	--	--	--
W27							--	--		--	--	--	--	--	--
W28							--	--	--	--	--	--	--	--	--
W29							--	--	--	--	--	--	--	--	--
W30							--	--	--	--	--	--	--	--	--
W31							--	--	--	--	--	--	--	--	--
W33								--	--	--	--	--	--	--	--
W34								--	--	--	--	--	--	--	--
W35													--	--	--
W36								--	--	--	--	--	--	--	--
Lagoon Monitoring Well Samples															
W20		--	*2*	7	--	--	--	--	--	--	--	--	--	--	
W21		4439	3195	10397	4533	2319	3113	935	1579	1014	1432	3848	1493	2963	4108
W22		8	57	6	2.8	4.5	62	481	129	90	59	144	32	90	90
W23		4.3	33	*1.4*	--	--	--	--	--	--	--	--	--	--	--

[a] Days after dye injection

[b] Background samples taken two days prior to dye injection

[c] Unconfirmed detection or indication in background sample

-- indicates non-detect

Blank indicates no sample

Table 6. Static water levels and relative ground-water elevations from the lagoon monitoring wells and relative surface-water elevations from the Big Sink Hole

Date	W20		W21		W22		W23		Big Sink Hole stage (ft)
	SWL (ft)	Elev (ft)	SWL (ft)	Elev (ft)	SWL (ft)	Elev (ft)	SWL (ft)	Elev (ft)	
4/21/04	26.87	77.21	24.49	77.34	26.96	77.31	26.76	77.03	3.22
4/27/04	26.29	77.79	24.05	77.78	26.45	77.82	26.13	77.66	>4.00
5/5/04	26.20	77.88	23.96	77.87	26.39	77.88	26.08	77.71	3.08
5/11/04	26.34	77.74	24.12	77.71	26.53	77.74	26.20	77.59	1.73
5/18/04	26.37	77.71	24.13	77.70	26.54	77.73	26.25	77.54	2.15
5/26/04	26.02	78.06	23.78	78.05	26.19	78.08	25.88	77.91	3.05
6/1/04	24.14	79.94	21.80	80.03	24.33	79.94	24.06	79.73	>4.00
6/8/04	22.90	81.18	20.67	81.16	23.16	81.11	22.77	81.02	>4.00
6/15/04	23.12	80.96	20.88	80.95	23.34	80.93	22.99	80.80	>4.00
6/22/04	23.32	80.76	21.09	80.74	23.54	80.73	23.21	80.58	>4.00
6/29/04	23.71	80.37	21.47	80.36	23.92	80.35	23.59	80.20	3.42
7/16/04	24.13	79.95	21.97	79.86	24.40	79.87	24.08	79.71	2.15
7/29/04	24.70	79.38	22.46	79.37	24.90	79.37	24.59	79.20	0.21
8/10/04	25.11	78.97	22.87	78.96	25.31	78.96	25.00	78.79	-0.40
8/26/04	25.56	78.52	23.32	78.51	25.74	78.53	25.45	78.34	-1.00
8/26/04	25.56	78.52	23.32	78.51	25.74	78.53	25.45	78.34	-1.00

Table 7. Apparent minimum groundwater flow velocities determined from fluorescein trace in sinkhole D55, calculated by the straight-line distance from sinkhole to well

Well	Transit Time[a] (days to first arrival)	Distance from Injection Point (ft)	Direction, Azimuth from Sinkhole D55 (°)	Velocity[a] (ft/day)
W06	*19*, 32	1720	223	54, *90*
W07	*53*, 84	1439	195	17, *27*
W10	*67*, 84	960	297	11, *14*
W19	125	5865	296	47
W20	*13*, 19	735	100	39, *57*
W21	≤4	69	85	≥17
W22	≤4	424	55	≥106
W23	≤4	1125	51	≥281
W25	*60*, 67	2519	207	38, *42*

[a] The italicized numbers refer to the first indication of dye in each well. The solid numbers indicate the first confirmed detections of dye.

Table 8a. Results of water quality analyses of lagoon, lagoon monitoring well, and Big Sink Hole water samples

Date	3/30	3/31	7/9	6/11	6/11	7/7	7/7	7/7	7/7	5/28	5/28	6/11	6/12	EPA[a]	MDH[b]
Sample ID	WS-1	Lagoon	Cell #1	Effluent	Bypass	W22	W21	W20	W23		Big Sink Hole			MCL	MCL
Laboratory	En Chem	U MN[c]	NTS[d]	NTS	U MN	NTS	NTS	NTS	NTS	NTS	U MN	NTS	U MN		
Conductivity (µhmos/cm)	610	--	446	409	--	258	96.3	94.4	135	31.3	--	59.2	--		
Total Solids (mg/L)	320	--	840	310	--	2650	713	537	810	580	--	107	--		
Total Suspended Solids (mg/L)	17	--	126	56.6	--	2660	734	592	946	160	--	1	--		
Total Dissolved Solids (mg/L)	260	--	268	191	--	162	15	87	67	52	--	94	--	*500*	
Volatile Solids (mg/L)	78	--	520	118	--	140	60	46.7	90	130	--	6.7	--		
Oil & Grease (mg/L)	<5.2	--	17.6	<2	--	--	--	--	--	3.1	--	<2	--		
Calcium (mg/L)	36	33.5	23.4	24	21.1	34.9	12.2	7.7	12.8	5.6	3.22	3.9	4.33		
Magnesium (mg/L)	5.8	5.48	4.9	4.6	4.6	17.9	8.4	4.2	8.3	1.9	1.07	1.4	1.5		
Sodium (mg/L)	64	59.1	47.4	42.3	43.2	10.3	5.1	5.5	6.6	1	0.765	4.3	4.78		
Potassium (mg/L)	15	14.9	8.6	9.8	8.95	6.9	4.8	4.3	4.1	2.7	2.11	3	2.73		
Silicon (mg/L)	--	3.52	--	--	6.6	--	--	--	--	--	3.94	--	1.49		
Total Alkalinity (mg/L)	190	--	97.1	92	--	94.6	40.1	26.6	39.8	6	--	10	--		
Fluoride (mg/L)	--	0.299	--	--	0.347	--	--	--	--	--	0.013	--	0.046	4	4
Chloride (mg/L)	67	70.2	63.1	56.4	54.9	19.6	5.2	9.4	14	1.1	0.37	6.6	5.271	*250*	
Bromide (mg/L)	<0.20	0.064	<0.1	0.48	0.02	0.12	0.39	<0.1	0.23	0.23	<0.005	0.44	0.002		
Orthophosphate -P (mg/L)	--	0.88	--	--	1.18	--	--	--	--	--	0.08	--	0.092		
Total P (mg/L)	2.3	1.317	9	1.8	1.57	1	0.9	0.33	0.49	0.24	0.136	0.37	0.2326		
Sulfate (mg/L)	--	5.01	--	--	12.26	--	--	--	--	--	1.87	--	2.766	*250*	
Kjeldahl-N (mg/L)	20	--	22.7	14.2	--	0.52	1.3	0.82	0.93	1.6	--	2.5	--	10	
NH4-N (mg/L)	16	15.52	6.7	5.7	5.01	0.14	<0.1	<0.1	<0.1	0.19	0.037	0.37	0.18		
NO3+NO2 as N (mg/L)	0.56	--	0.42	0.3	--	0.41	<0.1	<0.1	0.45	<0.1	--	0.18	--		
NO2-N (mg/L)	--	--	<0.01	0.12	0.97	0.02	0.02	0.01	<0.01	0.01	<0.01	0.01	0.017		
NO3-N (mg/L)	0.66	--	0.42	0.18	0.099	0.02	0.02	0.01	<0.01	<0.1	0.013	0.17	0.106		
Acetone (µg/L)	8	--	<20	--	--	--	--	--	--	--	--	--	--		700
Toluene (µg/L)	2.1	--	7.7	--	--	--	--	--	--	--	--	--	--	1000	1000
Acidity (mg/L)	<10	--	<1	<1	--		18	28	10	36	--	66	--		
Aluminum (µg/L)	<150	24.1	1130	239	52	21300	17600	5370	12400	4700	320	388	362	50-200	
Arsenic (µg/L)	<3.0	--	2	<2	--	3.7	2.8	<2	2.7	<2	--	<2	--	7	50
Barium (µg/L)	11	10.7	39.1	14.2	10.06	58.4	162	57.7	84.3	84.5	15.98	20.4	21.63	2	2
Beryllium (µg/L)	<1.0	--	<0.2	<0.2	--	1.1	0.8	0.2	0.5	<0.2	--	<0.2	--	4	4
Boron (µg/L)	150	--	250	181	--	<75	<75	<35	<35	50.4	--	<35	--		600
Cadmium, GF (µg/L)	<1.0	--	<0.2	<0.2	--	0.2	<0.2	<0.2	<0.2	0.3	--	<0.2	--	5	5
Chromium, GF (µg/L)	<3.0	--	4.6	2	--	49.4	48	15.7	19.3	4.6	--	1.4	--	100	100
Cobalt, GF (µg/L)	<2.0	--	1.2	1.2	--	18.2	13.3	3.7	6.3	1.4	--	<1	--		
Copper (µg/L)	<5.0	--	42.6	9.8	--	57.7	59.8	16.3	39.1	8.5	--	<5	--	1.3	
Iron (mg/L)	4.2	0.397	4.67	1.05	0.45	30.3	25.3	8.23	15.6	2.43	0.156	0.92	0.839	*0.3*	
Lead, GF (µg/L)	<2.5	--	4.1	<1	--	7.3	7.3	1.7	4.4	4.1	--	<1	--	0	
Manganese (mg/L)	0.89	0.496	0.65	0.3	0.12	0.41	0.78	0.17	0.22	0.35	0.03	0.04	0.0147	*0.05*	0.1
Nickel (µg/L)	<3.0	--	<5	<5	--	30.4	31	8.6	16.9	<5	--	<5	--		100
Strontium (µg/L)	--	55.1	--	--	52	--	--	--	--	--	17.53	--	17.96		
Tin, GF (µg/L)	<5.0	--	<10	<10	--	<10	<10	<10	<10	<50	--	<10	--		4000
Vanadium (µg/L)	<3.0	--	4.9	<4	--	56.9	52.1	17.3	28.9	5.9	--	<4	--		50
Zinc (µg/L)	420	--	404	31.1	--	189	101	26.7	38.5	56.9	--	23.9	--	*5*	2000
Fecal Coliform (#/100mls)	35	--	56	<400	--	4	50	4	<2	6	--	8	--	0	
TOC (mg/L)	18	--	26.1	22.4	--	4.6	9.7	9.5	3.3	18.8	--	29.2	--		
BOD (mg/L)	6	--	163	30.6	--	<2	<2	<2	<2	4.3	--	2.3	--		
CBOD (mg/L)	4.5	--	130	26	--	<2	<2	<2	<2	3.3	--	<2	--		
COD (mg/L)	71	--	508	378	--	11.2	25.5	24.2	8.2	41	--	85	--		

a U.S. Environmental Protection Agency
b Minnesota Department of Health
c University of Minnesota
d Northeast Technical Services

Table 8b. Results of water quality analyses of residential well drinking-water samples

Date	EPA[a]	MDH[b]	5/28/04	5/28/04	7/7/04	7/9/04	7/9/04	7/9/04	7/9/04	7/9/04
Sample ID	MCL	MCL	W01	W02	W02	W06	W10	W25	W26	W28
Laboratory			U MN[c]	NTS[d]	NTS	NTS	NTS	NTS	NTS	NTS
Conductivity (µhmos/cm)			--	198	189	240	178	143	169	142
Total Solids (mg/L)			--	137	127	147	96.7	56.7	83.3	90
Total Suspended Solids (mg/L)			--	0	11	9	7	2	<1	<1
Total Dissolved Solids (mg/L)	*500*		--	118	130	145	114	92	110	92
Volatile Solids (mg/L)			--	53.3	36.7	26.7	36.7	40	26.7	36.7
Oil & Grease (mg/L)			--	3.1	--	--	--	--	--	--
Calcium (mg/L)			20.4	20	17.6	22.7	15.7	12	16.6	11.3
Magnesium (mg/L)			7.51	7.2	6.7	8.5	5.7	4.6	5.8	5.2
Sodium (mg/L)			5.42	5	4.7	8.5	7	5.6	4.9	5.5
Potassium (mg/L)			2.4	2.9	2.7	1.8	2.9	3.1	3	3.3
Silicon (mg/L)			10	--	--	--	--	--	--	--
Total Alkalinity (mg/L)			--	66	61.4	82.6	65.4	45.4	60.8	48
Fluoride (mg/L)	4	4	0.05	--	--	--	--	--	--	--
Chloride (mg/L)	*250*		12.33	13.4	12.1	18.9	11.9	11.7	8.3	9.2
Bromide (mg/L)			0.0068	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Orthophosphate -P (mg/L)			0.022	--	--	--	--	--	--	--
Total P (mg/L)			0.032	<0.1	0.2	0.12	0.13	<0.1	<0.1	<0.1
Sulfate (mg/L)	*250*		5.5	--	--	--	--	--	--	--
Kjeldahl-N (mg/L)	10		--	<0.5	1.1	1.2	2.3	1	1.7	0.96
NH4-N (mg/L)			0.009	0.19	<0.1	<0.1	0.44	<0.1	<0.1	<0.1
NO3+NO2 as N (mg/L)			--	2.1	2	<0.1	<0.1	<0.1	0.81	0.51
NO2-N (mg/L)			<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NO3-N (mg/L)			2.433	2.1	2	<0.1	<0.1	<0.1	0.81	0.51
Acetone (µg/L)		700	--	--	--	--	--	--	--	--
Toluene (µg/L)	1000	1000	--	--	--	--	--	--	--	--
Acidity (mg/L)			--	<1	<1	<1	<1	4	<1	<1
Aluminum (µg/L)	50-200		4.9	<10	<10	<10	16.6	36.7	<10	16.6
Arsenic (µg/L)	7	50	--	<2	<2	2.4	<2	<2	<2	<2
Barium (µg/L)	2	2	35.9	34.4	31.2	35	37.3	32.8	33.3	30.3
Beryllium (µg/L)	4	4	--	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Boron (µg/L)		600	--	<35	<35	37.6	41.4	<35	<35	43.8
Cadmium, GF (µg/L)	5	5	--	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Chromium, GF (µg/L)	100	100	--	<1	<1	<1	1.6	<1	<1	<1
Cobalt, GF (µg/L)			--	<1	<1	<1	<1	1	<1	<1
Copper (µg/L)	1.3		--	22.3	16.1	5.8	<5	15.1	70.5	64.7
Iron (mg/L)	*0.3*		<0.01	<0.03	0.05	4.52	4.54	3.94	<0.03	0.03
Lead, GF (µg/L)	0		--	<1	1.4	<1	<1	<1	1.1	1.4
Manganese (mg/L)	*0.05*	0.1	0.0018	<0.01	<0.01	0.14	0.18	0.34	<0.01	<0.01
Nickel (µg/L)		100	--	<5	<5	<5	<5	<5	<5	<5
Strontium (µg/L)			43.1	--	--	--	--	--	--	--
Tin, GF (µg/L)		4000	--	<10	<10	<10	<10	<10	<10	<10
Vanadium (µg/L)		50	--	<4	<4	<4	<4	<4	<4	<4
Zinc (µg/L)	*5*	2000	--	41.4	69.3	51.7	16.4	16	<10	<10
Fecal Coliform (#/100mls)	0		--	<2	<2	<2	<2	<2	<2	<2
TOC (mg/L)			--	1.9	2.2	3	5.6	6.3	2.2	4.6
BOD (mg/L)			--	<2	<2	<2	<2	<2	<2	<2
CBOD (mg/L)			--	<2	<2	<2	<2	<2	<2	<2
COD (mg/L)			--	<1	7.5	7.5		13.5	4.5	12.9

[a] U.S. Environmental Protection Agency
[b] Minnesota Department of Health
[c] University of Minnesota
[d] Northeast Technical Services

Appendix A

Dye-Trace Tests

A-1 Dye-Trace Tests

1.1 Charcoal Detectors

Charcoal detectors were constructed by enclosing 4 g of activated carbon (Barnebey & Sutcliffe Type AC coconut shell carbon 6×12 mesh) in a 5-cm × 20-cm section of milk sock filter tube, stapled on both ends. A plastic tag was attached to the detector with a short piece of wire. This wire also served to attach the detector to a steel weight, which prevents the detector from washing away. In higher flow velocities, the weight was tied to a fixed object. Dyes were recovered in the laboratory by placing about 1 g (dry weight) activated carbon into a 16- × 100-mm disposable test tube and adding 8 mL of eluent. The remaining carbon was stored in a freezer for later re-analysis if required. The eluent used was a solution of 70% 2-propanol (CAS 67-63-0) and 30% de-ionized water saturated with sodium hydroxide (CAS 1310-73-2) (~10 g NaOH per liter of eluent), mixed in a 1-L separatory funnel to allow the dense phase, containing excess water and NaOH, to be discarded. The lighter phase is a NaOH-saturated solution of water and 2-propanol. The resulting eluent was scanned as a blank before proceeding with sample elution. After a one-hour extraction period, the resulting elutant was analyzed by pipetting 4 mL of elutant from the test tube into a 13- × 100-mm borosilicate glass vial with a screw cap.

1.2 Dye Analyses

The concentration of a number of Xanthene fluorescent dyes, including Sulforhodamine B (CAS 3250-42-1), Rhodamine WT (CAS 37299-86-8), Phloxine B (CAS 18472-87-2), Eosin Y (CAS 17372-87-1), and fluorescein, also named Uranine C (CAS 518-47-8), can be measured quantitatively with a spectrofluorophotometer. The analyses in this trace employed a Shimadzu RF-5000 scanning spectrofluorophotometer located in the Geology and Geophysics Department at the Minneapolis Campus of the University of Minnesota. All five dyes were measured simultaneously using a synchronous scan mode where the excitation and emission wavelengths were varied with a constant wavelength separation ($\Delta\lambda$) of 15 nanometers (nm). Excitation wavelengths were scanned from 385 nm to 635 nm; emission wavelengths were scanned from 400 nm to 650 nm at high sensitivity. Bandwidths for emission and excitation were set at 5 nm, and the scan rate is set at 30 nm/sec. $\Delta\lambda$ is optimized for Eosin, Phloxine, and Rhodamine WT, which have the poorest detection limits but have a maximum fluorescence response at $\Delta\lambda$ = 15 nm. Fluorescein response is slightly degraded but still has the lowest detection limit by an order of magnitude.

The resulting fluorescence spectra were saved to a text file. The Peakfit™ program, version 4.0, by Jandel Scientific, Inc., was used to separate the various components of the spectra. Peaks were fitted with a Pearson VII function; which empirically models both collisional and Doppler broadening of the fluorescence spectra. Peak area of a series of dye standards was used to create a calibration curve, based on the log area versus log concentration, for each dye.

Fluorescence of fulvic acids, humic acids, and chlorophyll were fit as background spectra. The proportion of fulvic and humic acids is often relatively constant for a given sampling point but varied significantly from sample to sample and in time in this trace. This background commonly formed a roughly concave-upward baseline that was not well approximated with a linear baseline. Fulvic acids have a broad (FWHM 60–80 nm) and highly tailed peak centered between 390 and 410 nm (excitation). Humic acids usually occur as a series of broad (FWHM 35–50 nm) peaks with centers at 25-nm intervals, starting with the largest at 450 nm and generally decreasing in area to about 550 nm. In the instrument used, chlorophyll forms a narrower peak located between 590 and 650 nm. Well-fitted dye spectra should have the statistical characteristics of an R^2 greater than 0.99 and an F-stat greater than 5,000.

The background peak fitting procedure started with the largest organic peaks and worked toward the wavelength range of interest as follows. First, a broad fulvic acid peak was fitted to the data, centered between 380 and 405 nm. The secondary tail (a2 parameter) of the fulvic peak may extend out to 600 nm with up to 80 nm FWHM and a2 < 1. Second, one or two chlorophyll-type peaks were fitted, as needed, between 590 and 650 nm. Some samples had no chlorophyll peaks. Third, humic acid peaks were added, starting with the 450-, 500-, and 575-nm peaks. For some samples, additional peaks were required around 475, 525, and 550 nm. The residuals were checked throughout the fitting process; ideal fits have random scatter at levels below 1%–2% of the peak heights. Systematic variation usually indicated a misfit or a missing peak. The goal throughout the fitting process was to use as few peaks as necessary to characterize the sample. More peaks can create a slightly better fit, but the point of diminishing returns is reached quickly, and the solution becomes non-unique. Samples suspected of containing dye were analyzed once the background spectra were well characterized. Xanthene dyes typically have FWHM of about 20 nm, which is distinct from most natural organics. Second, they generally have minimal secondary tails with an a2 parameter of 10, also different from the natural organics.

A wide range in the levels of background fluorescence was measured in samples collected for this study. This led to detection limits for both dyes that varied from place to place and varied with time at a specific place. The fluorescein analyses were particularly challenging, because many of the samples had a variable fluorescent background peak very near the fluorescene. The background peak was wider and could be distinguished from the fluorescein. A larger dye concentration is required to yield a **detection** if the background is high. Once a sampling station became positive for a dye, reanalysis of the preceding spectra from that station often yielded evidence of the dye below the detection limit of that analysis. These cases are called **indications** of dye and are indicated in the tables as *small italic numbers.*

1.3 Detecting and Quanitfying Dye Concentrations with PeakFit

By Scott C. Alexander, University of Minnesota

The process of quantifying xanthene dyes such as fluorescein, eosin, and Rhodamine WT using PeakFit non-linear curve fitting software is illustrated herein with examples from a dye trace at the Hiawatha (Hwy 55)/Crosstown (Hwy 62) intersection in Minneapolis, Minnesota. The test was conducted during the summer of 2002. All spectra presented are synchronous scans that are emission referenced with delta lambda of 15-nm and 5-nm bandwidths. The key concepts include definitions of baseline, instrumental noise, peak height, and peak width. Analytical definitions are from Long and Winefordner (1981) and Keith et al. (1983).

Figure A-1.1 shows a natural background spectrum prior to the introduction of any dyes. There is a total of 312 data points, one point every 0.8 nm from 400 to 650 nm. This density of data allows detailed resolution and separation of the background peaks from any dye peaks. These 312 data points form a generally concave-upward arc that is characteristic of the fluorescent organic acids that are present in natural waters.

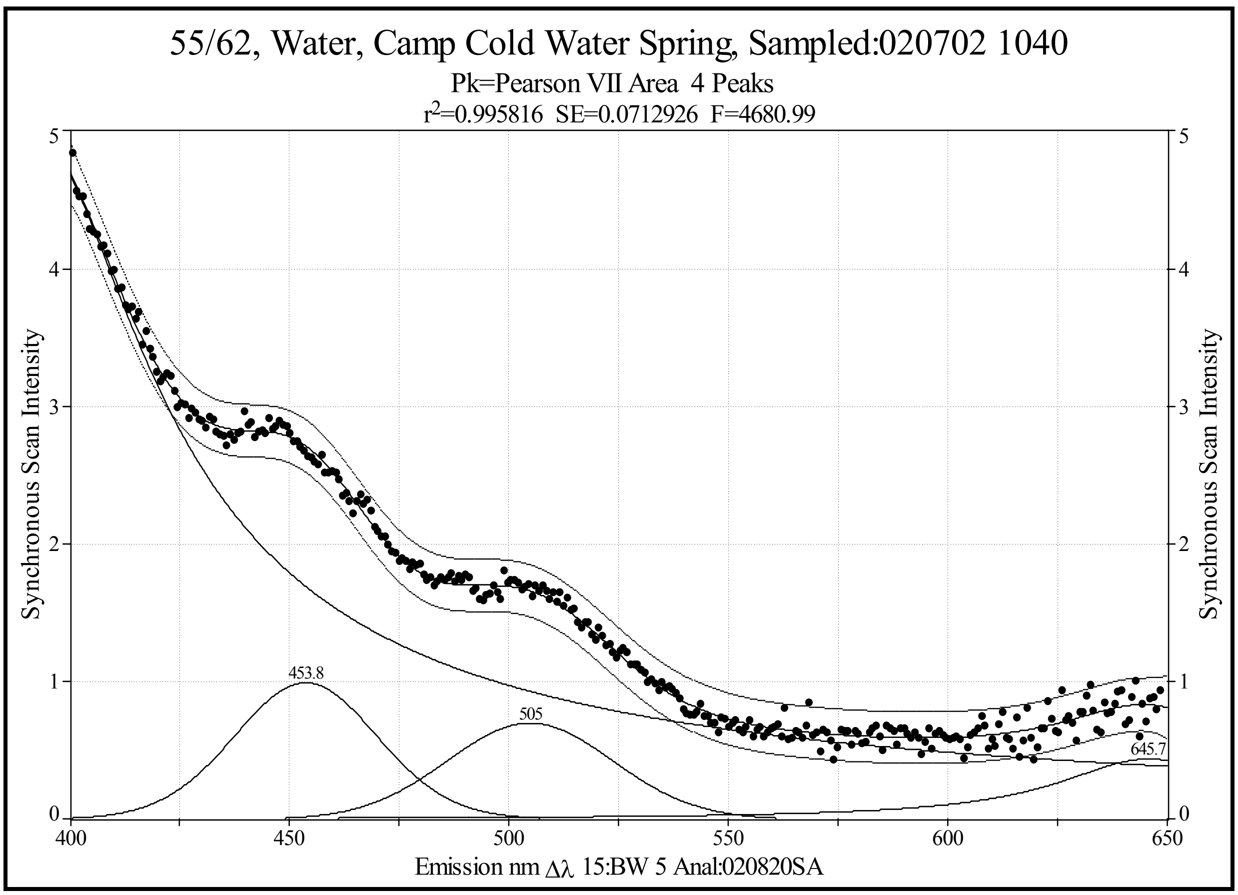

Figure A-1.1. An annotated example of background fluorescence from Camp Coldwater Spring.

Figure A-1.2 plots the instrumental noise as the difference between the observed data points and the modeled spectrum. In this example, the background noise has a normal distribution with a three-sigma probability estimate of plus or minus 0.21 intensity units. The Method Detection Limit is defined as:

Equation 1: MDL = 3 $\sigma_{background}$.

This assumes that any additional data points have a 99% probability of falling within 0.21 intensity units, or three σ, of the modeled background. This instrumental noise is a function of suspended sediment (scattered light), line spectra from the light source, Raman scattering, and internal voltage fluctuations.

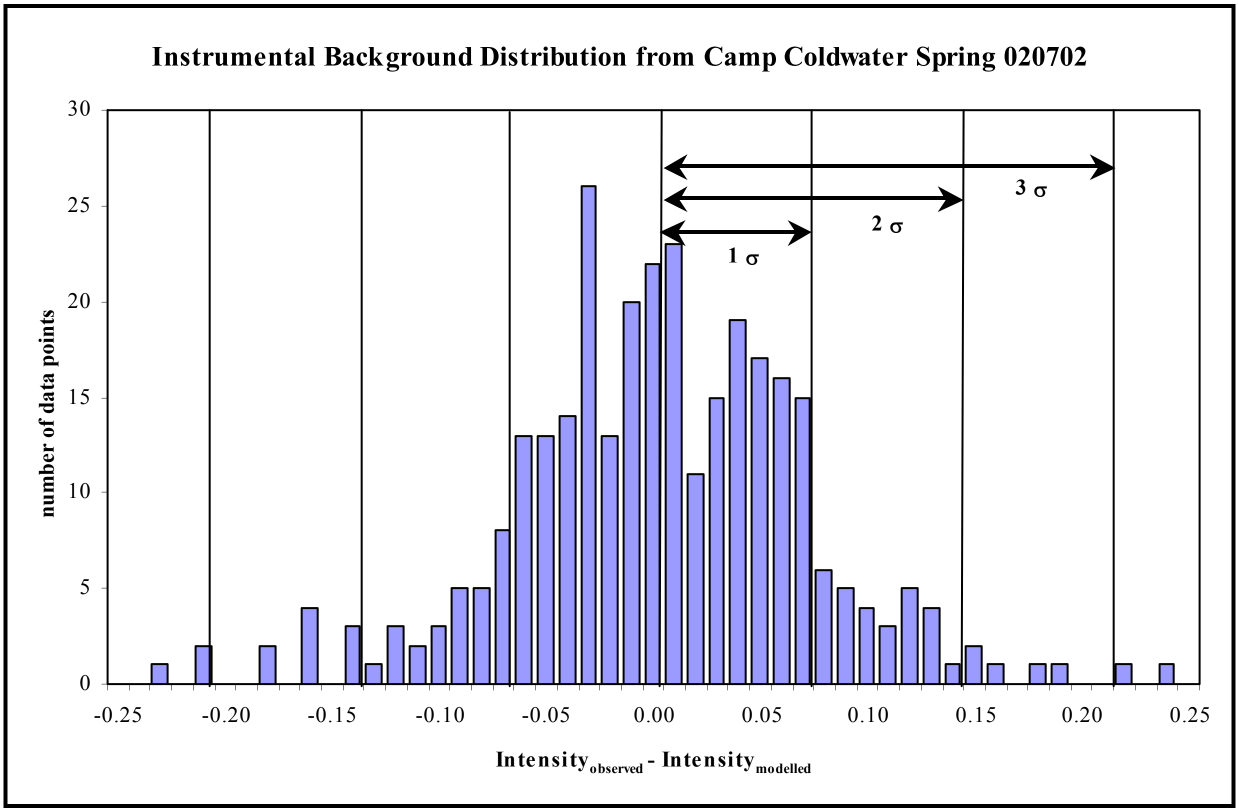

Figure A-1-2. Distribution of instrumental background noise for Camp Coldwater Spring.

The natural organics can be divided into three main categories: 1) fulvic acids, 2) humic acids and 3) chlorophylls. Fulvic acids generally create the largest and most highly tailed of the organic peaks with a peak center between 390 and 405 nm. Superimposed on the fulvic acids peak are two or more humic acid peaks with peak centers commonly at 450 and 505 nm. The humic acids are less tailed and typically have Full Width at Half Maximums (FWHM) in the range of 30 to 40 nm. Chlorophyll is usually centered near 650 nm and is generally narrower at higher concentrations. The mix of natural organics can be remarkably stable under relatively constant flow conditions.

The third figure shows two dye peaks, fluorescein and eosin, at quantifiable levels. The level of quantification is defined as:

Equation 2: $\mathbf{LOQ = 10\ \sigma_{background}}$.

In this example, a quantifiable dye concentration would be defined as peaks with a height of 10 times 0.07 intensity units or a peak height of 0.7 intensity units. From Figure 3 it can be seen that the fluorescein has a peak height of 1½ intensity units, and eosin has a height of 2¼ intensity units.

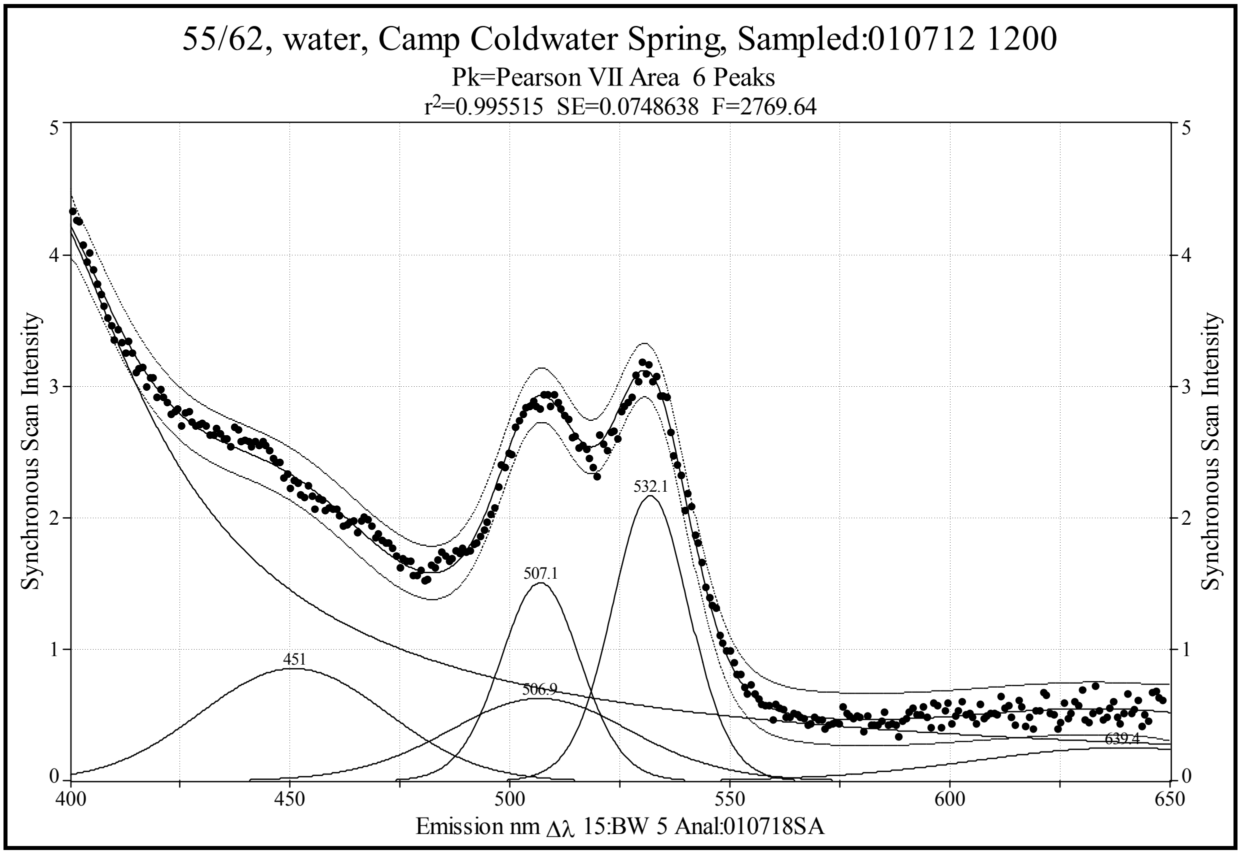

Figure A-1.3. Quantifiable fluorescein and eosin peaks on a background spectrum.

Dye concentrations can be calculated by comparing these peak heights, or preferably peak areas, to gravimetrically prepared standards. The peak area is a more robust estimator of dye concentration, as it is defined by more than 50 data points, whereas peak height is determined from a single data point. However, care should be taken to monitor the FWHM and the secondary tail of the dye peaks. Excessively wide or tailed peaks misrepresent the peak areas and lead to anomalously higher dye concentrations. These peak areas correspond to concentrations of 0.016ppb fluorescein and 0.176ppb eosin. Note that the instrumental background can be analyzed within a positive dye sample.

The fourth figure presents data from a sample long after the peak breakthrough concentration has passed. The levels of both fluorescein and eosin have fallen below quantifiable levels. Eosin is still readily quantifiable with a peak height of 1⅛ intensity units. Fluorescein has fallen to near the three σ probability estimate. Even at this level, the fluorescein still produces a peak statistically outside the modeled background spectrum. If this were a single sample and analysis the fluorescein peak would be very tenuous. This is particularly true if the 506-nm humic acid peak was allowed to compensate for the lack of a fluorescein peak.

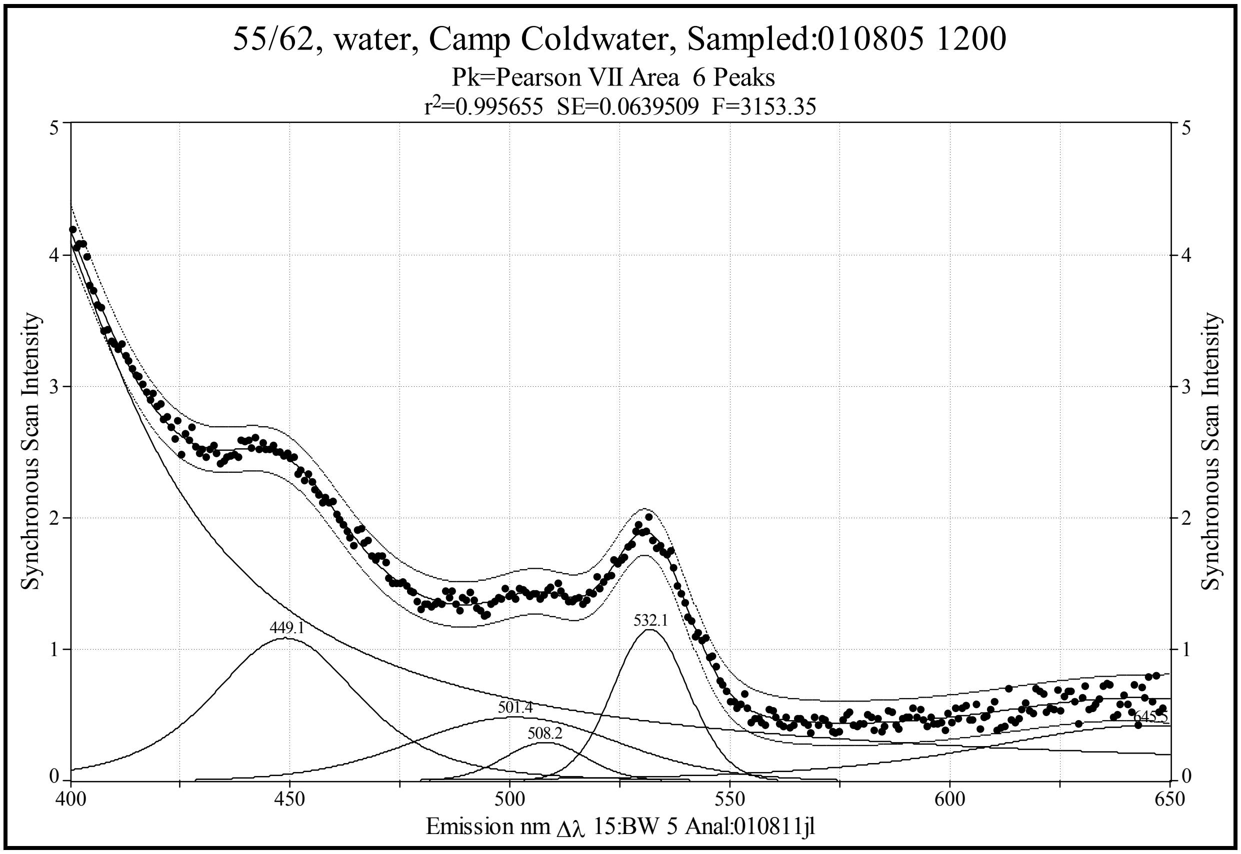

Figure A-1.4. Quantifiable eosin and detectable fluorescein peaks.

However, the great power of dye tracing is found in a systematic breakthrough curve. This means that a typical, positive dye trace is reproduced in a dozen if not hundreds of samples. A breakthrough curve creates an inherent reproducibility within a single dye trace. Where the background remains stable through the course of dye trace, the quantification limit drops in proportion to the number samples represented on the breakthrough curve:

Equation 3: $\sigma_{\mathbf{mean}} = \sigma_{\mathbf{background}} / \sqrt{\mathbf{n}_{\mathbf{samples}}}$

In the case of Camp Coldwater Spring, the background fluorescence has not significantly changed over the course of more than a month. Samples were initially collected at a rate of sixteen per day and scaled back to four per day after two weeks. This means that the August 5th sample represents the 240th sample collected on the fluorescein and eosin breakthrough curve. The fluorescein peak is significantly above the 10 σ_{mean} quantification limit of 0.14 intensity units. Because of the reproducibility inherent in the repetitive samples, fluorescein is still quantifiable for this example. The corresponding dye concentrations are: 0.003 ppb fluorescein and 0.089 ppb eosin.

In the main text of the report, the word "indications" corresponds to the "Level of Detection" (LoD), and the word "detections" corresponds to the "Level of Quantification" (LoQ).

1.1 References

Long, G.L., and J.D. Winefordner. 1983. The limit of detection: A closer look at the IUPAC definition. Analyt. Chem. 55:712A–724A.

Keith, L.H., W. Crummett, J. Deegan, Jr., R.A. Libby, J.K. Taylor and G. Wentler. 1983. Principles of environmental analysis. Analyt. Chem. 55:2210–2218.

Appendix B

Geophysical Investigations

GEOPHYSICAL SURVEY

ASKOV SEWAGE DISPOSAL PONDS

SEC. 29, T43N, R19W

PINE COUNTY, MINNESOTA

for

EXPONENT, INC.

by

R. J. IKOLA & ASSOCIATES, INC.

May 2004

This report, **GEOPHYSICAL SURVEY, ASKOV SEWAGE DISPOSAL PONDS, SEC. 29, T43N, R19W, PINE COUNTY, MINNESOTA**, was prepared as an independent geophysical evaluation for Exponent, Inc. All data were gathered and evaluated by Rodney J. Ikola, geophysicist for R. J. Ikola & Associates, Inc.

Rodney J. Ikola is a Professional Geologist in the state of Minnesota and a Registered Geophysicist in the state of California. He has in excess of 38 years of professional experience in geophysics.

All data acquisition and interpretation were done using standard and accepted methods. However, it is inherent in geophysics that two different solutions can satisfy the same set of data. The findings presented in this report are considered to be reasonable, but not the exclusion of alternative conclusions. Should more data become available, the opinions, findings and conclusions of this report are subject to change.

R. J. Ikola & Associates, Inc.

Rodney J. Ikola
Professional Geologist # 30211

3 May 2004

GEOPHYSICAL SURVEY
ASKOV SEWAGE DISPOSAL PONDS
SEC. 29, T43N, R19W
PINE COUNTY, MINNESOTA

SUMMARY

Electromagnetic (EM) and self-potential (SP) surveys were carried out in the vicinity of a sewage pond operated by the city of Askov. One line of EM run across a string of known sinkholes failed to detect any anomaly. However, an SP survey along the same line detected a characteristic low over the sinkholes. Based on this observation, a series of SP profiles were surveyed around the sewage pond resulting in several anomalous trends containing enhanced SP features suggesting the development of additional sinkholes.

INTRODUCTION

Geophysical surveys were conducted in the vicinity of the secondary sewage pond operated by the city of Askov. The purpose of these surveys was to evaluate their usefulness in detecting karst features that could have an impact on the safety of the ground water supply in the vicinity of the pond.

Previous geophysical studies have been conducted by Benson and Alexander (1998) to the NE of the present site. They concluded that EM (Geonics EM-31) and ground penetrating radar could be used successfully to image the subsurface conditions in their study area. However, their area is significantly different from that of the present study because of the overburden depths. Overburden depths encountered by Benson and Alexander were in the vicinity of 5 ft to 7.5 ft, significantly less than the 30± ft expected around the sewage pond. Based on that factor, different geophysical equipment was utilized in the present study.

EM readings were obtained with an Apex Parametrics MaxMin II+ system. This unit can operate at several different frequencies and also has the ability to obtain data from great depths (up to 400 to 500 ft vs the 15± ft with the EM-31). Although the usefulness of the radar data in the previous study cannot be dismissed, overburden depths at the present site present a serious problem. Also, ground conditions are unfavorable over portions of the site. Based on these considerations, the SP method was utilized at the pond site in an attempt to delineate areas impacted by karst development.

It was originally intended to conduct surveys on the bottom of the drained sewage pond. However, the sludge that had accumulated over a period of 40 years was deeper than anticipated and it proved impossible to try to wade through the morass.

SURVEY PROCEDURES

Electromagnetics

The EM survey was conducted in an attempt to see if the bedrock karst features could be directly detected. Overburden thickness ruled out the use of the Geonics EM-31. The deeper penetrating Geonics EM-34 operates at a relatively low frequency of 1645 Hz so it was decided to use an Apex Parametrics MaxMin II+ system which has both higher frequencies and greater depth capabilities.

Both the EM-31 and –34 measure the quadrature component of the electromagnetic field and that in turn is internally converted to conductivity units using certain assumptions. The MaxMin system also measures the quadrature component but the measuring unit is a percentage of the primary transmitting field. Although the results are displayed in different units, both units measure the same component of the electromagnetic field.

A transmitter-receiver separation of 150 ft was used for the MaxMin survey, using frequencies of 1777 Hz and 3555 Hz.

Self-Potential

The SP survey was conducted using a single base station located at line 0E, station 0. Liquid junction electrodes using a copper element immersed in a copper sulfate solution contained within a pot with a porous ceramic base were used for making contact with the ground. A high input impedance digital multimeter manufactured by Fluke was used for measuring the voltage difference between the base station and the field station. Wire to connect the two pots was contained on a reel that was moved from station to station.

A third electrode was used as a reference to check for drift and polarization in the base and field electrodes. Procedures as described by Applegate et al (1982) were used to correct for polarization and drift.

Readings were generally taken at intervals of 25 ft. Holes were dug several inches below the surface to make contact with naturally moist soil.

INTERPRETATION OF RESULTS

Electromagnetics

Results of the electromagnetic survey are shown on the enclosed graph. Reading accuracy is about ±0.5 %.

The line crosses between two sinkholes located near station 0. There is absolutely no indication of increased conductivity associated with these features. A wet swamp causes a slight anomaly centered at 200S. Notice the better response at the higher frequency.

Self-Potential

SP methods have had modest use in environmental and engineering applications. Mostly this limited use appears to result from a lack emphasis at the educational level. However, it is a well known physical phenomenon that when a fluid is forced to flow through a porous medium voltage potentials are often produced. The US Army Corps of Engineers has done considerable research on the SP method, especially for detecting leakage through dams and for locating karst features (Erchul and Slifer, 1989). Negative SP anomalies are generally found over these karst features.

The SP results are shown on the colored contour map with the locations of the measuring points shown by dots. The outline of the sewage pond is indicated and the location of a monitoring well near the NW corner of the pond is also shown.

A contour interval of 5 millivolts was used for constructing the map. During the survey, 10 stations were repeated and the maximum discrepancy was 3 millivolts after polarization and drift corrections were made.

The area of known sinkholes is centered around station 010N, line 210W, in a noticeable SP low. Other prominent SP lows which may indicate the presence of additional sinkholes are located at:

- Line 0E, 075N
- Line 075S, 225E to 250E This is an extremely prominent feature located on the berm between the two lagoons. Indications of this feature can also be seen on line 200E, 050S to 075S and along the east end of line 0N.
- Line 0E, 425S This feature was only detected on the last reading on this line so the center of the anomaly may actually be farther south. Some caution is warranted because the anomalous station is located next to a fence with metal posts. If any corrosion is occurring at the post this could be a cultural anomaly. Obtaining several more readings to the south of the fence should be considered before additional investigations are conducted on this feature.

The entire portion of line 0E along the west edge of the pond is low and there are several additional features that could indicate increased karst development along this stretch. A monitoring well just off the NW corner of the pond is located at the northern end of this low area and the records from this boring should be examined to see if any indication of karst development is present. If karst formation is present in this boring, there may be a significant zone of karsting along the west edge of the pond.

Another trend of low SP readings extends from the known sinkholes on line 210W along a curvilinear trend to the prominent SP low at the east end of line 075S. Only additional fill in lines can determine if this trend is continuous.

Originally it was planned to survey the bottom of the pond when it was drained. However, the sludge that had accumulated for many tens of years was too thick to allow any easy way of doing this. If it becomes necessary again to consider surveying the pond, the use of a shallow draft boat and electrodes suitable for offshore work should be considered.

This survey may be considered to be of a reconnaissance nature, given the potential size of any sinkhole. If the present results prove to be of value, closer line spacing may be necessary to fully evaluate the site. In the cleared areas around the ponds this would proceed rather rapidly. However, the brushy area to the west of the pond would impede progress considerably because of the need for cut lines.

CONCLUSIONS

EM techniques do not appear to be of value in directly detecting the karst features. In the previous study by Benson et al they were of use because the edge of the pollution plume, as mapped by the EM-31, occurred over the edge of a karst feature (into which it was draining?). As such, the EM technique located the karst feature in an indirect manner.

The SP method was able to identify the location of sinkholes known to exist on the property. Additional SP features, which are strongly suspected to indicate additional sinkholes, need to be investigated further. If these features are proven to be caused by karsting, a denser grid of SP readings may be warranted.

It needs to be emphasized that SP results tend to be diffuse in nature. Any karst feature associated with an SP anomaly will probably be smaller that the areal extent of the geophysical response.

REFERENCES CITED

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Benson, M. A. and Alexander, E. C., 1998, Geophysics, Near Surface Characterization, Rocky Kroon Farm Site-Partridge Township, Report submitted to Pine County Soil and Water Conservation District.

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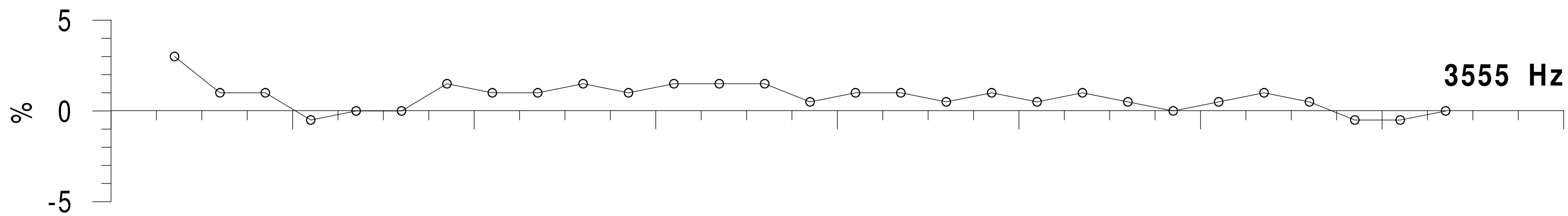
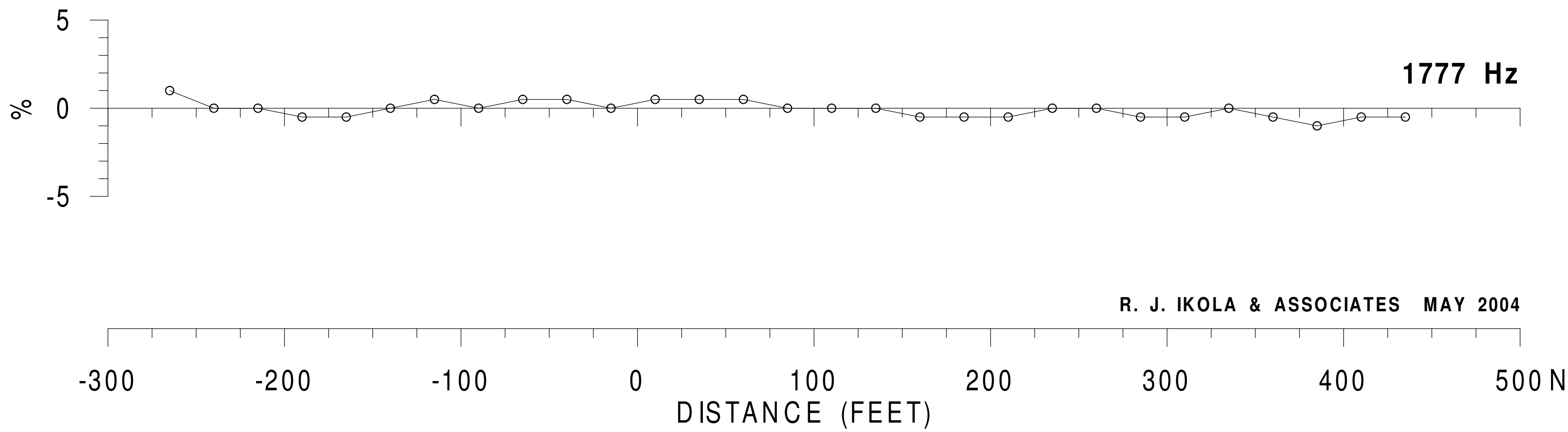
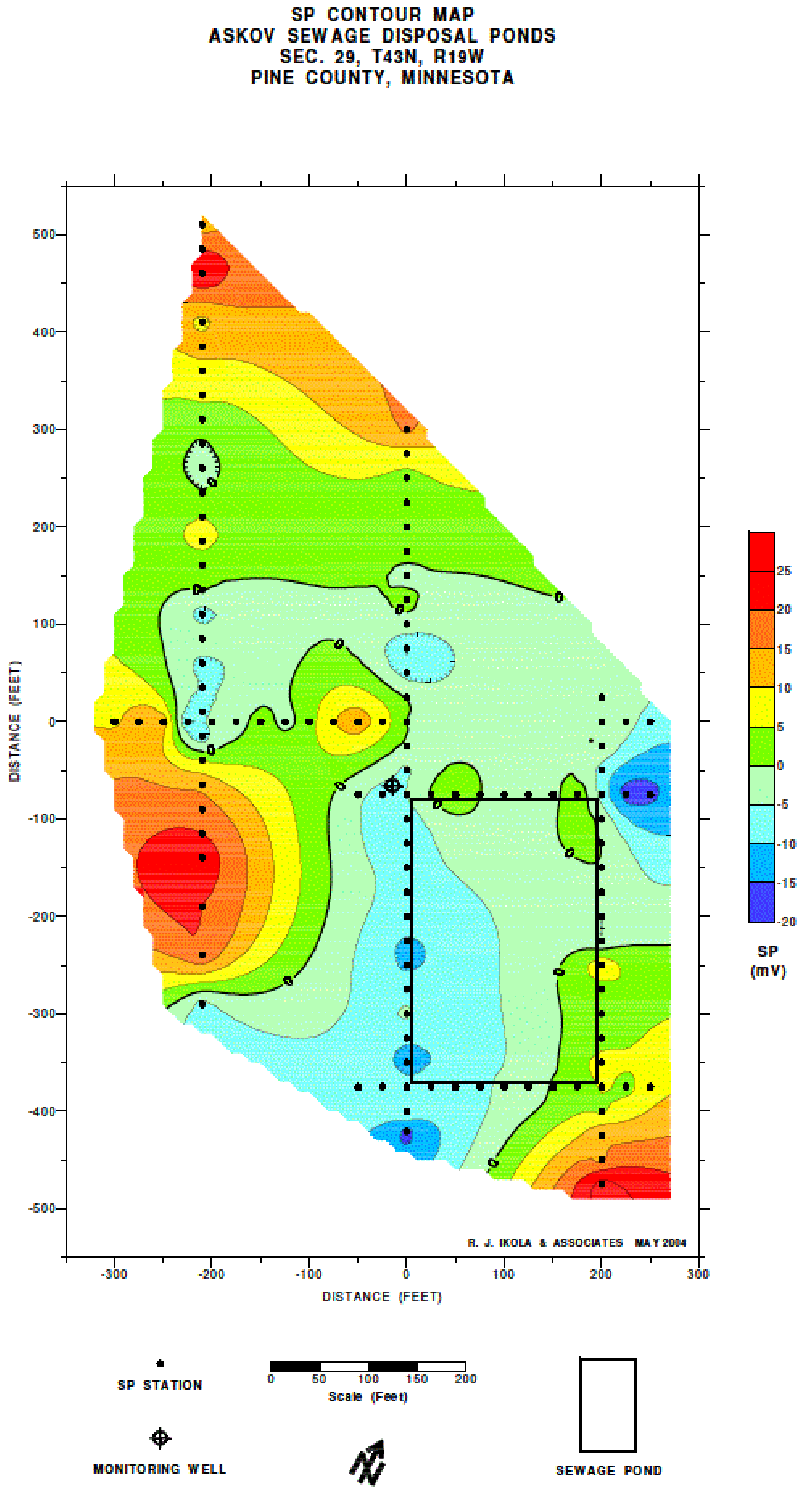
MAXMIN II+ EM SURVEY
ASKOV SEWAGE DISPOSAL PONDS
LINE 210W
SEC. 29, T43N, R19W
PINE COUNTY, MINNESOTA



Quadrature Component
Coil Separation: 150 feet



R. J. IKOLA & ASSOCIATES MAY 2004


SP CONTOUR MAP
ASKOV SEWAGE DISPOSAL PONDS
SEC. 29, T43N, R19W
PINE COUNTY, MINNESOTA
DISTANCE (FEET)
DISTANCE (FEET)
SP
(mV)
R. J. IKOLA & ASSOCIATES MAY 2004
SP STATION
MONITORING WELL
Scale (Feet)
SEWAGE POND

SELF-POTENTIAL SURVEY

ASKOV SEWAGE DISPOSAL PONDS

SEC. 29, T43N, R19W

PINE COUNTY, MINNESOTA

for

EXPONENT, INC.

by

R. J. IKOLA & ASSOCIATES, INC.

August 2004

This report, **GEOPHYSICAL SURVEY, ASKOV SEWAGE DISPOSAL PONDS, SEC. 29, T43N, R19W, PINE COUNTY, MINNESOTA**, was prepared as an independent geophysical evaluation for Exponent, Inc. All data were gathered and evaluated by Rodney J. Ikola, geophysicist for R. J. Ikola & Associates, Inc.

Rodney J. Ikola is a Professional Geologist in the state of Minnesota and a Registered Geophysicist in the state of California. He has in excess of 38 years of professional experience in geophysics.

All data acquisition and interpretation were done using standard and accepted methods. However, it is inherent in geophysics that two different solutions can satisfy the same set of data. The findings presented in this report are considered to be reasonable, but not the exclusion of alternative conclusions. Should more data become available, the opinions, findings and conclusions of this report are subject to change.

R. J. Ikola & Associates, Inc.

Rodney J. Ikola
Professional Geologist # 30211

3 May 2004

GEOPHYSICAL SURVEY
ASKOV SEWAGE DISPOSAL PONDS
SEC. 29, T43N, R19W
PINE COUNTY, MINNESOTA

SUMMARY

Electromagnetic (EM) and self-potential (SP) surveys were carried out in the vicinity of a sewage pond operated by the city of Askov. One line of EM run across a string of known sinkholes failed to detect any anomaly. However, an SP survey along the same line detected a characteristic low over the sinkholes. Based on this observation, a series of SP profiles were surveyed around the sewage pond resulting in several anomalous trends containing enhanced SP features suggesting the development of additional sinkholes.

INTRODUCTION

Geophysical surveys were conducted in the vicinity of the secondary sewage pond operated by the city of Askov. The purpose of these surveys was to evaluate their usefulness in detecting karst features that could have an impact on the safety of the ground water supply in the vicinity of the pond.

Previous geophysical studies have been conducted by Benson and Alexander (1998) to the NE of the present site. They concluded that EM (Geonics EM-31) and ground penetrating radar could be used successfully to image the subsurface conditions in their study area. However, their area is significantly different from that of the present study because of the overburden depths. Overburden depths encountered by Benson and Alexander were in the vicinity of 5 ft to 7.5 ft, significantly less than the 30± ft expected around the sewage pond. Based on that factor, different geophysical equipment was utilized in the present study.

EM readings were obtained with an Apex Parametrics MaxMin II+ system. This unit can operate at several different frequencies and also has the ability to obtain data from great depths (up to 400 to 500 ft vs the 15± ft with the EM-31). Although the usefulness of the radar data in the previous study cannot be dismissed, overburden depths at the present site present a serious problem. Also, ground conditions are unfavorable over portions of the site. Based on these considerations, the SP method was utilized at the pond site in an attempt to delineate areas impacted by karst development.

It was originally intended to conduct surveys on the bottom of the drained sewage pond. However, the sludge that had accumulated over a period of 40 years was deeper than anticipated and it proved impossible to try to wade through the morass.

SURVEY PROCEDURES

Electromagnetics

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A transmitter-receiver separation of 150 ft was used for the MaxMin survey, using frequencies of 1777 Hz and 3555 Hz.

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The SP survey was conducted using a single base station located at line 0E, station 0. Liquid junction electrodes using a copper element immersed in a copper sulfate solution contained within a pot with a porous ceramic base were used for making contact with the ground. A high input impedance digital multimeter manufactured by Fluke was used for measuring the voltage difference between the base station and the field station. Wire to connect the two pots was contained on a reel that was moved from station to station.

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INTERPRETATION OF RESULTS

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Results of the electromagnetic survey are shown on the enclosed graph. Reading accuracy is about ±0.5 %.

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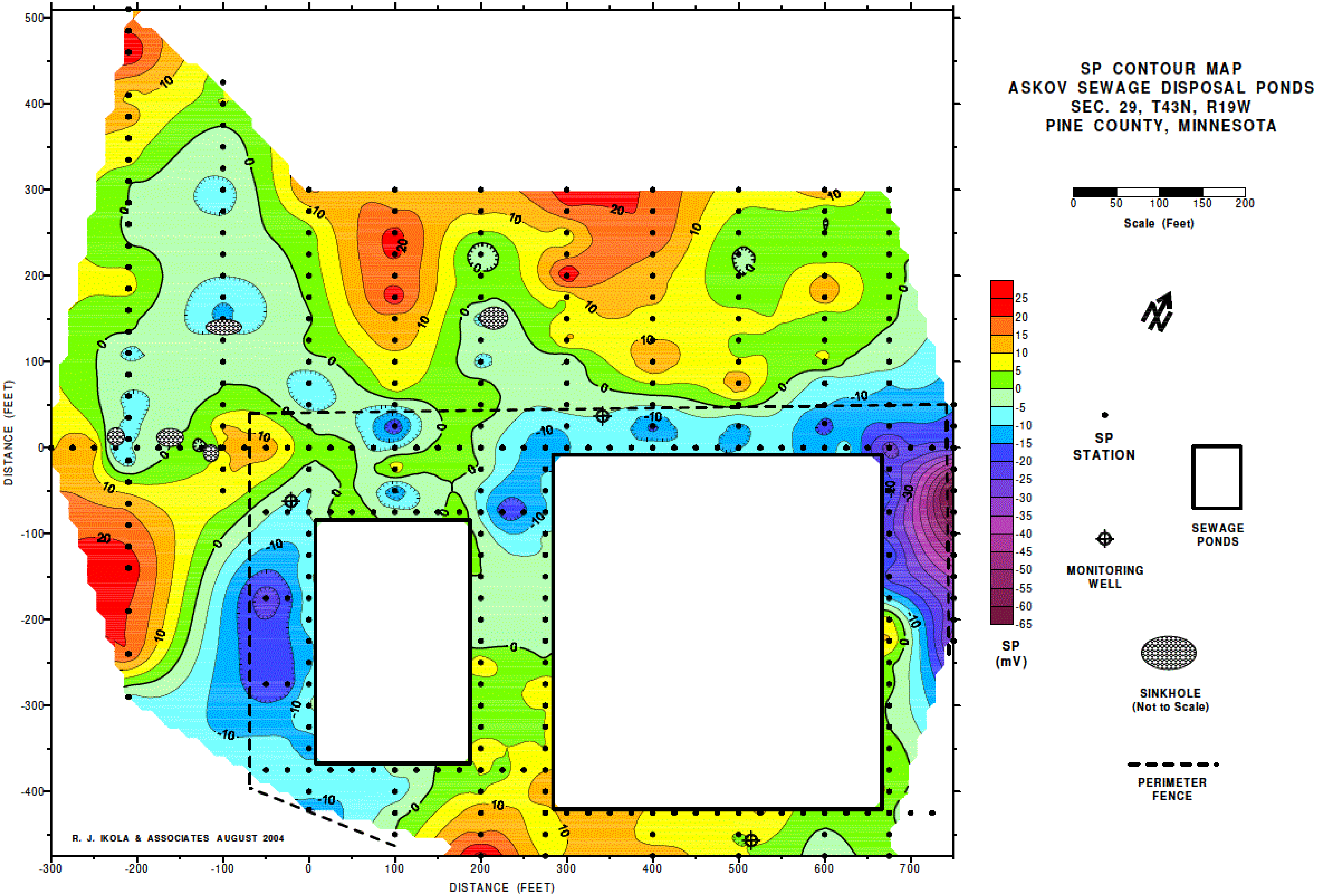
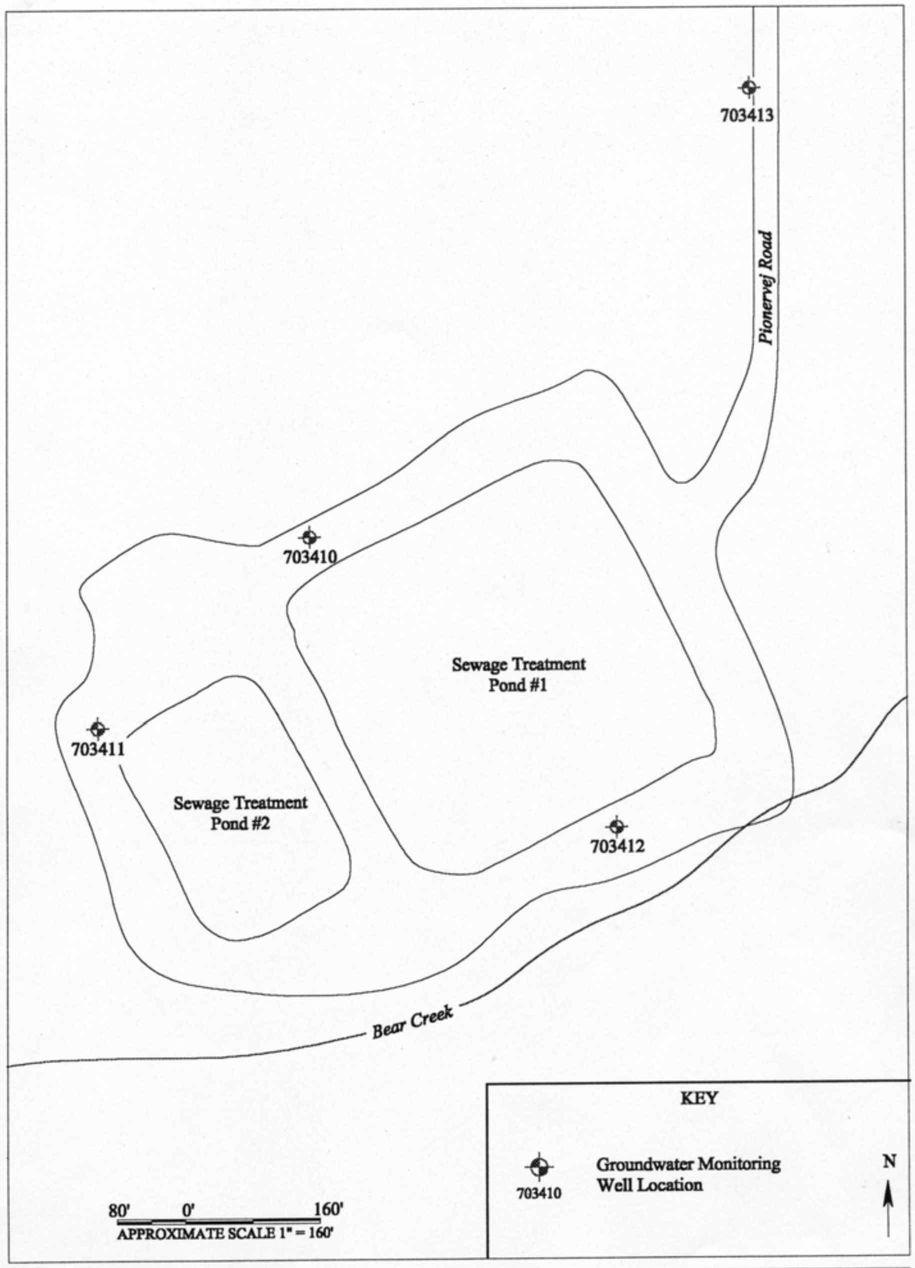

SP CONTOUR MAP
ASKOV SEWAGE DISPOSAL PONDS
SEC. 29, T43N, R19W
PINE COUNTY, MINNESOTA
0 50 100 150 200
Scale (Feet)
25 20 15 10 5 0 -5 -10 -15 -20 -25 -30 -35 -40 -45 -50 -55 -60 -65
SP
(mV)
SP
STATION
MONITORING
WELL
SEWAGE
PONDS
SINKHOLE
(Not to Scale)
PERIMETER
FENCE
DISTANCE (FEET)
DISTANCE (FEET)
R. J. IKOLA & ASSOCIATES AUGUST 2004

Appendix C

Monitoring Well Logs



WCEC ENVIRONMENTAL CONSULTANTS	Detailed Site Map	Figure 2
	Askov Sewage Treatment Ponds - Askov, MN	Project #: 04-4520-30

BORING LOG

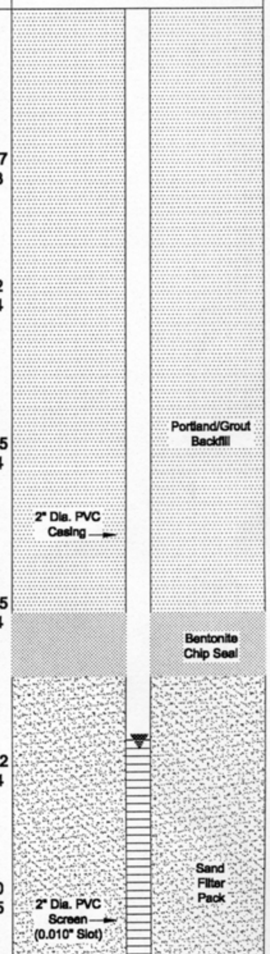
Well Number: 703410

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/13/04 10:40
DATE/TIME COMPLETED: 4/15/04 10:30
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time
0	~6" Grasses & Organic Material							
5	CLAYEY SAND (SC): fine grained sand; subrounded; fragments of basalt,sandstone, and slate; reddish-brown; moist to wet; low plasticity							10:47 4/13
10				NR				9:42 4/14
	Layer of cobbles from 12'-14' bgs consisting of sub rounded particles of basalt, granite, and slate approximately 1"-6" in diameter.							10:25 4/14
15	SANDY CLAY (CL): fine grained sand; subrounded grains; fragments of slate (2-5 mm dia.); reddish-brown; moist; high plasticity							
20	SAND (SP): fine grained sand; subrounded grains; fragments of slate; slight clay content; intermingling silt lenses (light brown); moist; non-plastic Saturated at 22' bgs					23.35'		10:45 4/14
25								11:32 4/14
	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist							9:10 4/15
30								

Well Construction Diagram



WCEC
ENVIRONMENTAL CONSULTANTS

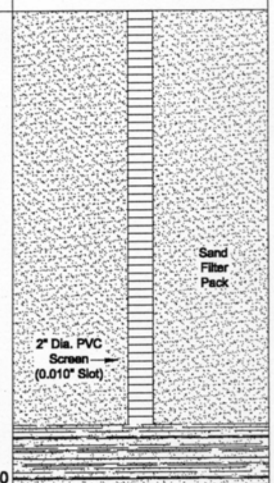
BORING LOG

Well Number: **703410**

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/13/04 10:40
DATE/TIME COMPLETED: 4/15/04 10:30
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time	Well Construction Diagram
30	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist								
35									
40									
45	End of boring at 45' bgs							10:30 4/15	
50									
55									
60									



WCEC ENVIRONMENTAL CONSULTANTS

BORING LOG

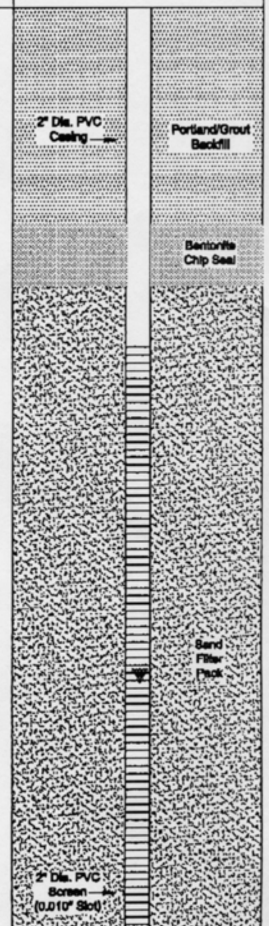
Well Number: **703411**

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/14/04
DATE/TIME COMPLETED: 4/15/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time
0	~6" Grasses & Organic Material							
0–15	CLAYEY SAND (SC): fine grained sand; subrounded; fragments of basalt,sandstone, and slate; reddish-brown; moist to wet; low plasticity							
15–25	SAND (SP): fine grained sand; subrounded grains; fragments of slate; slight clay & silt content; orange-yellow; moist; non-plastic							
	Saturated at ~22' bgs					21.86'		
25–30	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist							
	Possible fracture in sandstone formation from 28'-30' - auger bit dropped ~2 feet and hole would not clear.							

Well Construction Diagram



WCEC ENVIRONMENTAL CONSULTANTS

BORING LOG

Well Number: 703411

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/14/04
DATE/TIME COMPLETED: 4/15/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time	Well Construction Diagram
30	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist								
35									
40									
45	End of boring at 45' bgs								
50									
55									
60									

WCEC
ENVIRONMENTAL CONSULTANTS

BORING LOG

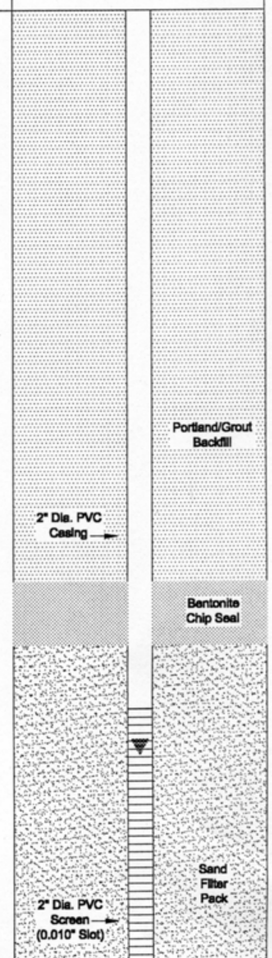
Well Number: **703412**

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/15/04
DATE/TIME COMPLETED: 4/16/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time
0	~6" Grasses & Organic Material							
0–15	CLAYEY SAND (SC): fine grained sand; subrounded; fragments of basalt,sandstone, and slate; reddish-brown; moist to wet; low plasticity							
15–22.5	SAND (SP): fine grained sand; subrounded grains; fragments of slate; slight clay & silt content; orange-yellow; moist; non-plastic							
22.5–30	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist					23.55'		

Well Construction Diagram



WCEC ENVIRONMENTAL CONSULTANTS

BORING LOG

Well Number: 703412

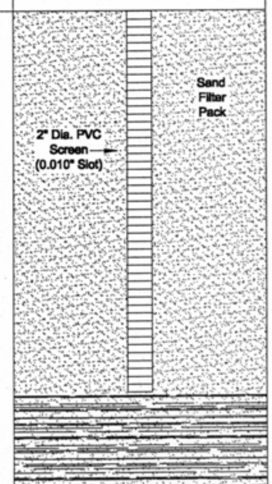
LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/16/04
DATE/TIME COMPLETED: 4/16/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time
30–45	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist							
45	End of boring at 45' bgs							

Depth scale: 30, 35, 40, 45, 50, 55, 60

Well Construction Diagram



WCEC ENVIRONMENTAL CONSULTANTS

BORING LOG

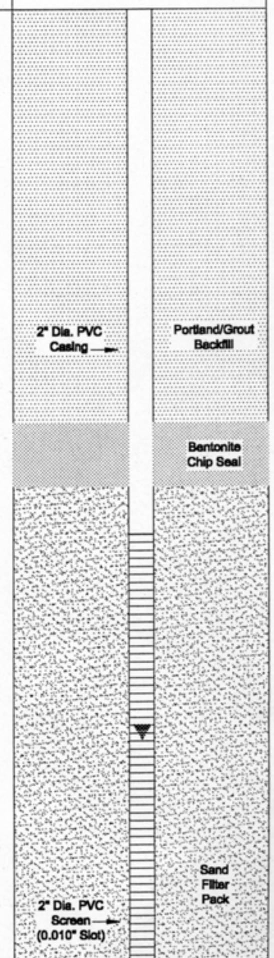
Well Number: **703413**

LEAK NUMBER: N/A
PROJECT NUMBER: 04-4520-30
PROJECT NAME: Askov Sewage Treatment Ponds
DRILLER: Stevens Drilling & Environmental, Inc.
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/20/04
DATE/TIME COMPLETED: 4/20/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time
0	~6" Grasses & Organic Material							
0–15	CLAYEY SAND (SC): fine grained sand; subrounded; fragments of basalt,sandstone, and slate; reddish-brown; moist to wet; low plasticity							
15–22.5	SAND (SP): fine grained sand; subrounded grains; fragments of slate; slight clay & silt content; orange-yellow; moist; non-plastic					23.13'		
22.5–30	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist							

Well Construction Diagram



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BORING LOG

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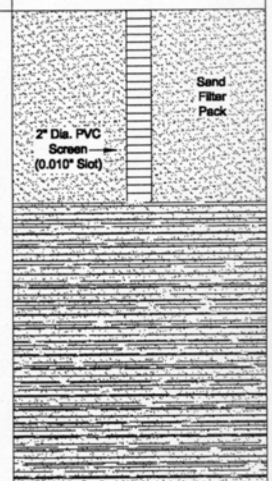
DRILLING METHOD: Air Rotary

PERSONNEL: SE
DATE/TIME STARTED: 4/20/04
DATE/TIME COMPLETED: 4/20/04
SURFACE ELEVATION: N/A
BACKFILL METHOD: Well Installed

Depth (ft-bgs)	Material Description	USCS Symbol	Attempted	Recovered	Blow Count	GW Level	PID (ppm)	Time	Well Construction Diagram
30–45	SANDSTONE BEDROCK: yellow-brown; fine to medium grains; moist								
45	End of boring at 45' bgs								
50									
55									
60									



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